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WRIGHT-PATTERSON AIR FORCE [illegible]

EFFECTS OF EXIT GEOMETRY AND EXTERNAL AIR FLOW ON THE PERFORMANCE OF A PULSEJET ENGINE

THESIS

Presented to the Faculty of the Resident College of
the United States Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the
Graduate Diploma

By

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2nd Lieut. USAF

2 GAE 55

30 August 1955

Foreword

This report was prepared as an independent study by the author as a graduate student in the Mechanical Engineering Department of the Air Force Institute of Technology, Wright-Patterson Air Force Base. The initial idea for this project was suggested by R. W. McJones, Chief Powerplant Engineer for the American Helicopter Company. Work on this subject was carried out from 1 January 1955, to 1 August 1955, under the able guidance of Professor Andrew J. Shine of the Mechanical Engineering Department. Valuable assistance on this project was rendered by 1st Lt. Edward T. Pitkin of the Powerplant Laboratory, Wright Air Development Center, and Wallace V. Lukey of the Mechanical Engineering Laboratory, United States Air Force Institute of Technology, both of Wright-Parrerson Air Force Base.

Abstract

A 5.0-inch diameter pulsejet engine was tested under static and velocity conditions with various tail exit angles varying from a 30° convergence to 45° divergence. The optimum operating angle was obtained in terms of thrust and thrust specific fuel consumption. The use of average combustion chamber pressure as an indicator of thrust was ascertained and the effect of velocity upon this correlation was studied. Hot and cold engine drag were obtained for various ram air velocities. An attempt was made to use exhaust gas temperature as a thrust indicator. All results are shown in graphical form.

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EFFECTS OF EXIT GEOMETRY AND EXTERNAL AIR FLOW ON THE PERFORMANCE OF A PULSEJET ENGINE

I. Introduction

This report describes testing procedures and results of experiments upon the performance parameters of a 5.0-inch diameter pulsejet engine which was made by the American Helicopter Division of Fairchild Engine and Airplane Corporation, Manhattan Beach, California.

This item provides for the selection of an optimum tailpipe exit angle for the engine, under both static and velocity conditions. Tailpipe sections varying from a 10° convergence to a 45° divergence were tested under various ducted air speeds. Results are shown in terms of net thrust developed, thrust specific fuel consumption, and combustion chamber pressure for the different tail sections and the various air velocities, which range from static to 125 feet per second.

This report also substantiates the correlation between the engine operating parameters "net thrust" and "combustion chamber pressure". Evidence of this correlation was first introduced by the American Helicopter Company (Ref. 1). A correlation of thrust with some easily obtained engine parameter is very desirable. The pilot of an aircraft in flight could then have an instrument in the cockpit to indicate engine thrust under any flight conditions. However, limitations were found which impair the usefulness of this correlation as a means of thrust indication.

A study was made to determine the effect of ram air upon engine thrust, thrust specific fuel consumption, and the relation between net thrust and combustion chamber pressure. (Hereafter, "thrust" will refer to "net thrust", and "gross thrust" will be written as such.) In this test, hot drag was determined and cold drag was found both with and without the engine cowling for ram air velocities ranging from static to 100 feet per second.

In connection with the above major study topics, an attempt was made to find a relation between exhaust gas temperature, and thrust and fuel consumption. Also, a limited study was made to find the effect upon fuel consumption of a 6-inch diameter duct over the tailpipe.

II. Experimental Equipment and Instrumentation

The Engine

The engine which has been tested is a 5.0-inch diameter pulsejet whose shell and tailpipe are made of Inconel X. The engine and the thrust stand are shown in Figure 1. Figure 2 shows a schematic drawing giving the basic dimensions of the engine.

A 5.0-inch length was removed from the end of the tailpipe and other sections of the same length, but with different exit angles, were made to replace it. The tailpipe which was originally on the engine had a $12\frac{1}{2}^{\circ}$ divergence. The other exit angles used had a 0°, 5°, 20°, 30°, and 45° divergence and 10°, 15°, 25°, and 30° convergence. These sections, along with the original, are shown in Figure 3. The tailpipe sections were first held together with a high temperature silver solder but finally had to be reinforced with spot-welded strips due to the fact that the high temperatures encountered were melting the silver solder. The 5.0-inch sections were attached to the engine with hoseclamps.

Supporting Facilities

Fuel System. The fuel (JP-4) was supplied to the engine at a controlled pressure of 100 pounds per square

inch. The flow of fuel was regulated with a valve in the fuel line and a flow meter (precision bore flow rator, tube number B3A-25). The calibration curve for this flow meter is shown in Figure 4. The fuel entered the combustion chamber through a nozzle and then a struck a baffle plate and was further diffused. The nozzle and baffle plate are shown clearly in Figure 5. (Note that the mirrowed view shows the inlet valves of the engine.) The American Helicopter Company (Ref. 2) conducted tests on this engine to determine the optimum location of the baffle plate and the best fuel injection system for the engine. It might be mentioned that the location of the baffle plate in relation to the nozzle is quite critical with regard to maximum thrust.

<u>Air Supply System</u>. Compressed air at a pressure of 100 pounds per square inch was supplied to a turbine which was geared directly to a compressor (turbo-supercharger unit). The air flow used for testing was supplied by this compressor. The velocity of the air flow was sufficiently high without the burning of fuel in the combustion chamber before the turbine, even though such facilities were available. The air supplied by the compressor was ducted through a 6-inch diameter pipe and used for testing under various conditions. Some of the compressed air which was used to drive the turbine was used for cooling the combustion chamber of the pulsejet engine and for starting purposes. Two

cooling tubes were used to direct streams of air directly on the combustion chamber. This cooling effect probably decreased the overall effectiveness of the engine, but was necessary to prevent overheating the engine in the wide range of performance imposed during the tests. The starting air was supplied to the engine through a tube mounted on the test stand in front of the engine. This tube is shown in Figure 1.

Apparatus for Ducted Air

The ducting system and pressure probe for measuring air flow velocities are shown in Figure 6. The pressure lines were connected to an inclined manometer. Tests were made with each tail section at air velocities of 0, 25, 50, 75, 100, and 125 feet per second, and each test was run from a very lean fuel setting to rich flameout. The pressure probe was long enough to extend well beyond the diverging section of the tailpipe so that the flow in that region might be considered parallel.

Apparatus for Ram Air

The ducting system for testing under ram air conditions is shown in Figure 7. The engine was run with the $12\frac{1}{2}^{\circ}$ tail section at ram air velocities of 0, 29, 52, and 98 feet per second, both with and without its cowling. Again each test was made between lean fuel settings and

rich flameout. Since it was difficult to use the pressure probe to determine air velocity, the velocity was first calibrated as a function of turbine revolutions per minute. This calibration curve is shown in Figure 8. The turbine revolutions per minute were read from a tachometer which was geared to the turbine. Neither the tachometer nor the turbine fuel and air controls are shown in the array of instruments and controls of Figure 9.

It was impossible in this test to use the original starting air system because of the location of the ram air duct. Also, the built-in system of the engine (Ref. 2) failed to give sufficient air to start the engine. The engine was started by using the high velocity ram air of the ram air ducting system.

Instrumentation

To measure the average combustion chamber pressure of the engine, a pressure line from a tap in the combustion chamber was connected to a water manometer. The operating frequency of the engine was so high that the pressure indication was quite steady under good operating conditions.

The thrust was measured with four strain gages, which were mounted on two cantilever beams (a strain gage on each side of both beams) and connected so that the recording would indicate only bending stresses in the beams,

which corresponds to engine thrust or drag. The strain gages and beam arrangement are shown in an enlarged view in Figure 10 and also in Figures 1 and 7. The bridge circuit is shown on top of the stand in Figure 7. Due to the intermittent and high frequency firing of the engine, a well damped recording instrument was needed to measure average thrust. The Foxboro Baldwin Strain Recorder (Fig. 9) was an ideal instrument. Its recordings were inked on a slowly revolving circular disc and the instrument was accurate to less than one-half pound of thrust. A calibration was made with weights and the curve is shown in Figure 11.

Exhaust gas temperatures were measured with a thermocouple mounted at the engine exit (Fig. 6). The readings were obtained from a Brown Electric Pyrometer which measured up to 2000° F. At times this maximum temperature was exceeded.

A two channel pyrometer was used to find the temperature indicated by two thermocouples mounted on the beams beside the strain gages. The purpose of these strain gages was to ascertain the effect of the temperature on the thrust measurements.

III. Discussion of Results

The tail sections with angles of 15°, 25°, and 30° convergence proved unsatisfactory for engine operation. The engine could not be started when these sections were used. The ability of converging tubes to operate was questioned by Schultz and Grunow in "Gas-Dynamic Investigations of the Pulsejet Tube" (Ref. 3) as the result of a theoretical analysis. However, the 10° converging section did operate but gave very low thrust. All of the other tail sections (all divergent) operated satisfactorily.

The operating frequency of the engine varied from 122 to 181 cycles per second (Ref. 2:11). The frequency was highest at lean fuel settings and decreased as fuel was increased until after the fuel setting for maximum thrust. Then, if the engine did not flame out, the frequency would again rise rapidly, along with a sharp drop in thrust and combustion chamber pressure. So the engine had the same operating frequency both at very lean and very rich fuel flows.

It should be mentioned that the tests were run on different days under different atmospheric conditions. The exact correlation of atmospheric change with engine operation is not known. However, an attempt was made to test on the same day runs which would be closely compared.

Static Conditions

Combustion chamber pressures versus fuel flows are plotted in Figure 12 for the static engine. This curve indicates that pressure rises with increasing fuel flow and reaches a maximum at a fuel flow of 70.0 pounds per hour with a 20° tail section, while Figure 13 (Thrust vs Fuel Flow under static conditions) indicates a maximum thrust at the same fuel flow with the 12½° tail section. This seems to imply a fallacy in the proposed correlation between thrust and combustion pressure. A plot of the two parameters (Fig. 14) shows, however, an almost linear relationship. Figure 14 also shows the reason for the suspected discrepency above. Since the lines of the 12½°, 20°, 30°, and 45° tail sections are almost parallel, the combustion chamber pressure is higher for a given thrust at higher exit angles. If the 30° or 45° sections had given equal thrusts, the combustion pressure would have been even higher. In Figure 14 and several other figures of thrust versus combustion chamber pressure, the darkened points indicate data taken after maximum performance was reached. The operation of the engine was usually very erratic under these conditions and both thrusts and combustion pressures varied rapidly. These readings, therefore, are probably not as accurate as those taken in going from a lean fuel setting to the optimum.

Figure 15 indicates that for minimum thrust specific

fuel consumption, the 20° and 5° sections are almost as good as the 12½° section. However, the 12½° section has a lower thrust specific fuel consumption over a wider fuel range, and the curve does not break as sharply as the curve of the 5° section after maximum thrust has been reached. There could possibly be some section between the 12½° and the 20° section that would give the optimum performance. However, it must be concluded, that of the sections tested, the 12½° section gives the best performance. Other points of interest in Figure 15 are the low fuel ranges of the 0° and -10° (10° convergence) sections. It is also noticeable that when the exit angle exceeds 20°, the performance falls off with increasing exit angle. The flatness of the curves indicate that the engine has the trait of constant thrust specific fuel consumption at maximum thrust and also at lower thrust values. However, operation at the point of maximum thrust (fuel flow is 70.0 pounds per hour) could be critical because the rapid changes in the curves after this point indicate that increased fuel flow would result in either a sudden drop in thrust or rich flameout.

Tests Using Ducted Air Around the Tailpipe

These tests simulated flight conditions around the exit of the engine without considering the increase or decrease in engine performance due to ram air in the front of the engine. This ducting system (Fig. 6) was used in order

to hold other variables constant while making a study of the effect of exit geometry on engine operation with air flow over the exit. The maximum ducted air velocity of 125 feet per second does not compare with flight speeds, but the velocity was limited by the maximum turbine RPM.

Figures 16, 17, 18, 19, 20, and 21 show the best tail angle in terms of thrust for ducted air velocities of 0, 25, 50, 75, 100, and 125 feet per second respectively for various fuel flows. While the $12\frac{1}{2}^{\circ}$ section gives the best performance under most conditions, this is not always the case. In Figure 18 (velocity = 50 feet per second), the 20° section gives maximum thrust at both 70.0 and 63.5 pounds per hour fuel consumption and Figure 19 (velocity = 75 feet per second) indicates that the 30° section gives maximum thrust at both 50.0 and 43.3 pounds per hour fuel consumption.

The curves of Figures 22, 23, 24, 25, and 26 show thrust specific fuel consumption versus fuel consumption for tail angles of 0°, 5°, $12\frac{1}{2}^{\circ}$, 20°, and 30° respectively at various ducted air velocities. The $12\frac{1}{2}^{\circ}$ tail section (Fig. 24) and the 30° section (Fig. 26) appear to have the lowest thrust specific fuel consumption over a wide range of fuel flows for the most air speeds. However, the 20° section (Fig. 25) also has a low thrust specific fuel consumption and at one point (fuel flow = 63.5 pounds per hour) has the lowest reading of any tail section. There

seems to be a strong trend for the thrust specific fuel consumption to increase as the ducted air velocity increases. However, due to some unknown changes in operating conditions, the trend is not followed in some cases (Fig. 24, for example).

The curves of Figures 27, 28, 29, 30, and 31 show thrust versus fuel consumption for the various tail angles under ducted air velocity conditions. The thrust, in most cases, decreases with increasing air velocity for any given fuel flow. The maximum thrust of 18.1 pounds was obtained using a 5° tail section at no velocity and a fuel flow of 70 pounds per hour (Fig. 28). However, the thrust at velocity for the 5° section falls off rapidly. On the other hand, the 12½° section gives only 17.8 pounds of thrust at maximum, but the thrust is almost the same for a wider range of velocities.

The 0° tail angle (Fig. 27) gives a good example of the decrease in thrust with the increase in velocity and also shows the poor thrust qualities and small operating range of this tail section.

Thrust versus combustion chamber pressure was plotted for the various tail sections (Fig. 32, 33, 34, 35, and 36) with all points recorded at all velocities to see if a correlation between the two parameters would hold at any speed. The figures prove the validity of the assumption. The points follow a narrow linear band, and an average line, in most

cases, would miss an outside point by only one pound of thrust for any given combustion pressure. This average line is not, however, the static line which is drawn on the graphs. The 0° section (Fig. 32) shows such poor operating characteristics that no attempt was made to find a correlation.

<u>Tests Using Ram Air</u>

This study was made to find the effect of ram air on thrust, thrust specific fuel consumption, and the correlation between net thrust and combustion chamber pressure. Figure 39 indicates a definite loss in net thrust due to the engine drag caused by the ram air (about 16% loss of maximum thrust at a velocity of 98 feet per second). However, at increasing fuel flows the ram air apparently gives better combustion. There seems to be equalization between increased thrust due to better combustion and decreased thrust due to drag at a ram air velocity of 52 feet per second where the thrust is 1.3 pounds greater than at no ram air.

The minimum thrust specific fuel consumption changes very little with changes in ram air velocities (Fig. 40). However, at low fuel flows, the ram air is definitely detrimental to the thrust specific fuel consumption.

Figure 41 shows the effect of ram air on the net thrust-combustion pressure relationship. The lines are

parallel and it is easy to see just how much the ram air drag decreases the net thrust for a given combustion chamber pressure.

Hot Drag. The hot drag is defined as the difference between the gross thrust and the net thrust of an engine in operation in ram air. Figures 42 and 43 show the hot drag for two ram air velocities. The net thrust is easily measured with the strain gage arrangement, but it is more difficult to obtain gross thrust. Since it has been shown that the thrust-combustion pressure relationship is valid, this correlation is used in obtaining gross thrust. First, a net thrust and combustion pressure are obtained under ram air conditions. Then for this combustion pressure a thrust (which corresponds to gross thrust) is read from a curve where the ram velocity is zero. The difference in these two thrust measurements is hot drag and is practically constant for the entire fuel flow range. In Figure 41 the difference in thrust between any velocity line and the static line is the hot drag at that particular velocity.

Cold Drag. The cold drag is defined as the drag caused by ram air on an engine which is not in operation. The engine cowling was removed in an effort to reduce this drag and a slight reduction was noted (Fig. 44). However, the engine thrust was lower without the cowling under all ram velocities (Fig. 45). Evidently, the cowling ducts

the air into the engine inlet valves and this effect improves engine performance.

Changes in Engine Performance Due to Unavoidable Changes in the Engine

The pulsejet engine will change performance with the slightest provocation. Figure 37 shows thrust versus fuel flow for various engine operating conditions. Run number 2 was made after the valves in the engine used in run number 1 had been replaced by new ones. Run number 3 was made after the engine of run number 2 had its fuel baffle plate straightened. At all times an attempt was made to match the original conditions. However, the maximum thrust dropped from 16.2 pounds to 13.4 pounds and the fuel range decreased considerably. The fact that these changes affected the correlation between thrust and combustion pressure is shown in Figure 38. This means that every time the engine valves became worn or the engine was repaired, a new correlation for thrust indication would have to be found.

Effect of a Ducted Tailpipe on Fuel Consumption

A limited attempt was made to find the effect on fuel flow of a 6-inch duct (ejector configuration) around the engine tailpipe as some reports indicate a decrease in fuel flow with ducted engines. Figure 46, however, indicates a slight increase in fuel consumption for all values of thrust when the engine is ducted. This is not meant to condemn

ducted engines. This author appreciates the fact that a different size duct and/or a different location of the duct along the horizontal axis of the engine might give beneficial effects.

Exhaust Gas Temperatures

The exhaust gas temperatures showed no consistency in their relationship with thrust and fuel flow. The most common trend was a decreasing temperature as fuel consumption and thrust increased up to the maximum thrust. Then, right before rich flameout, the temperature would rise again. The exhaust gas temperatures varied from 1450° F. to over 2000° F.

It was noticeable that the tail angle of 10° convergence, which gave the lowest thrust, ran at much higher exhaust temperatures than the other sections. The temperatures could not be recorded since they were always over the maximum of the 2000° F. pyrometer. The tail section giving the next highest temperatures was the 0° or straight section, which also had rather poor thrust characteristics. This seems to indicate that low thrust is associated with high exhaust temperatures. However, the other exit angles tested showed almost the same exhaust temperatures irregardless of their thrust.

The use of exhaust gas temperature as an indication of engine performance seems impractical. For example, a high

temperature before rich flameout could give a very erroneous indication if the engine operator did not know whether he was on the lean or rich side of the optimum fuel setting. Another disadvantage is the fact that the temperature at the exhaust might be affected considerably by the external environment.

Effect of Heat on Thrust Measurements

The thermocouples mounted beside the strain gages showed a room temperature of 86° F. Maximum temperatures during engine operation were 102° F. on the front beam and 116° F. on the rear beam. In order to determine the effect of this temperature rise on the strain gages and thus the thrust measurements, the beams were preloaded and heat was applied to the base of the beams with a blow torch. As the temperature varied from 85° F. to 115° F., the load measurement remained constant. It is therefore to be concluded that the temperature had no effect on the accuracy of the strain gages or the thrust measurements.

IV. Conclusions

1. The $12\frac{1}{2}^{\circ}$ diverging tail angle gave the best overall performance of the sections tested under both static and velocity conditions. However, there may be some angle between $12\frac{1}{2}^{\circ}$ and 20° which would give even better performance.

2. The use of exhaust gas temperature as a thrust indicator is not recommended because of the inconsistent correlation between the two parameters.

3. Combustion chamber average pressure is a good indicator of engine thrust under static and velocity conditions. However, some calibration factor would have to be provided for each engine configuration and checked periodically during the life of the engine.

4. The thrust- combustion pressure correlation could be misleading, since low pressure indicates low thrust at both lean and rich fuel flows.

5. A small and unavoidable change in the physical engine necessitates a new calibration factor (combustion pressure-thrust) for the engine.

6. Ram air decreases the net thrust of the engine because of the increase in engine drag.

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2. Lockwood, R.M. and Thomas, C.H. Development and Sea-Level Static Tests of American Helicopter Five-Inch Diameter Pulsejets. American Helicopter Report No. 1949 B-401, 1 July 1954.

3. Shultz, F. and Grunow. Gas-Dynamic Investigations of the Pulsejet Tube. NACA Technical Memorandum No. 1131 February 1947.

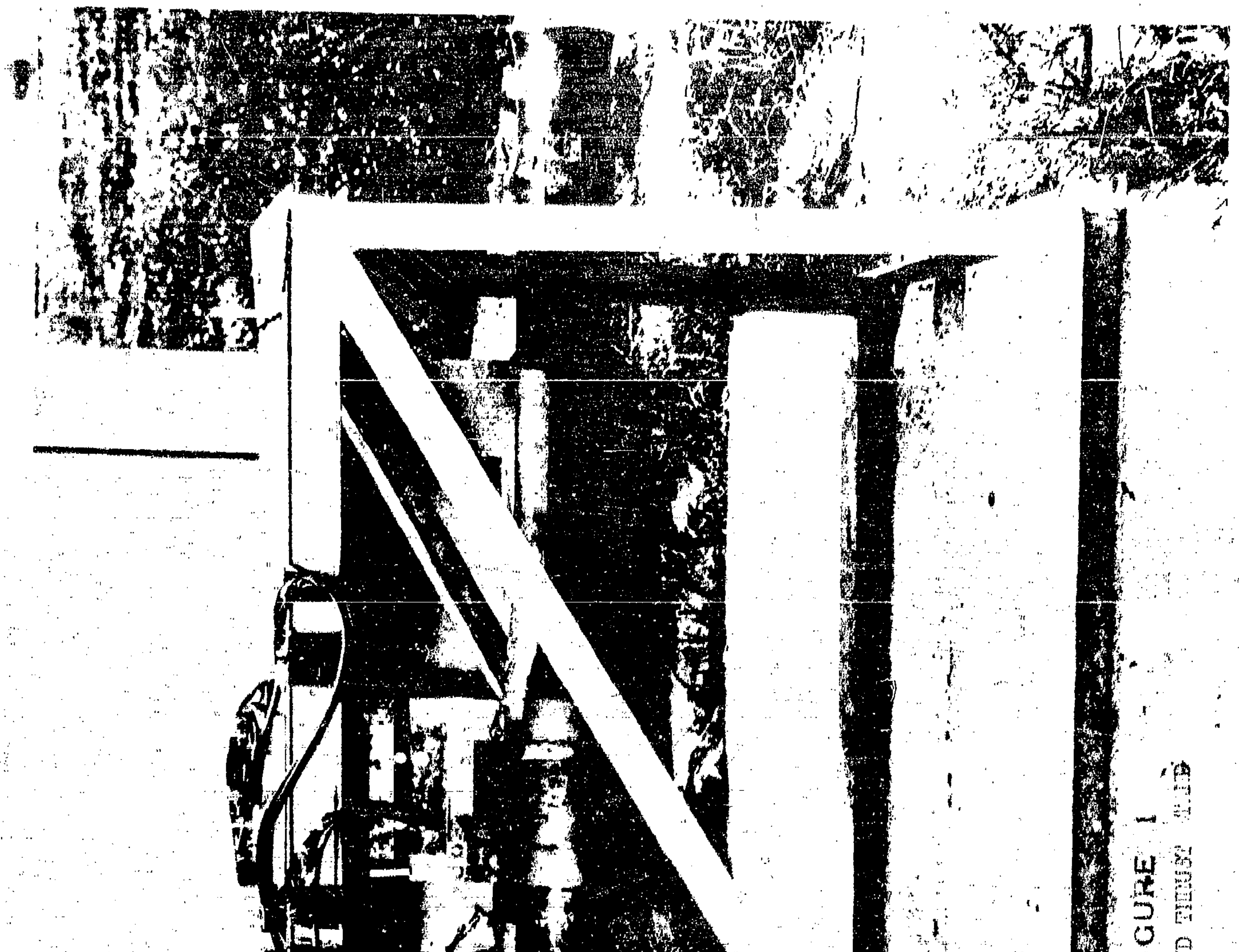
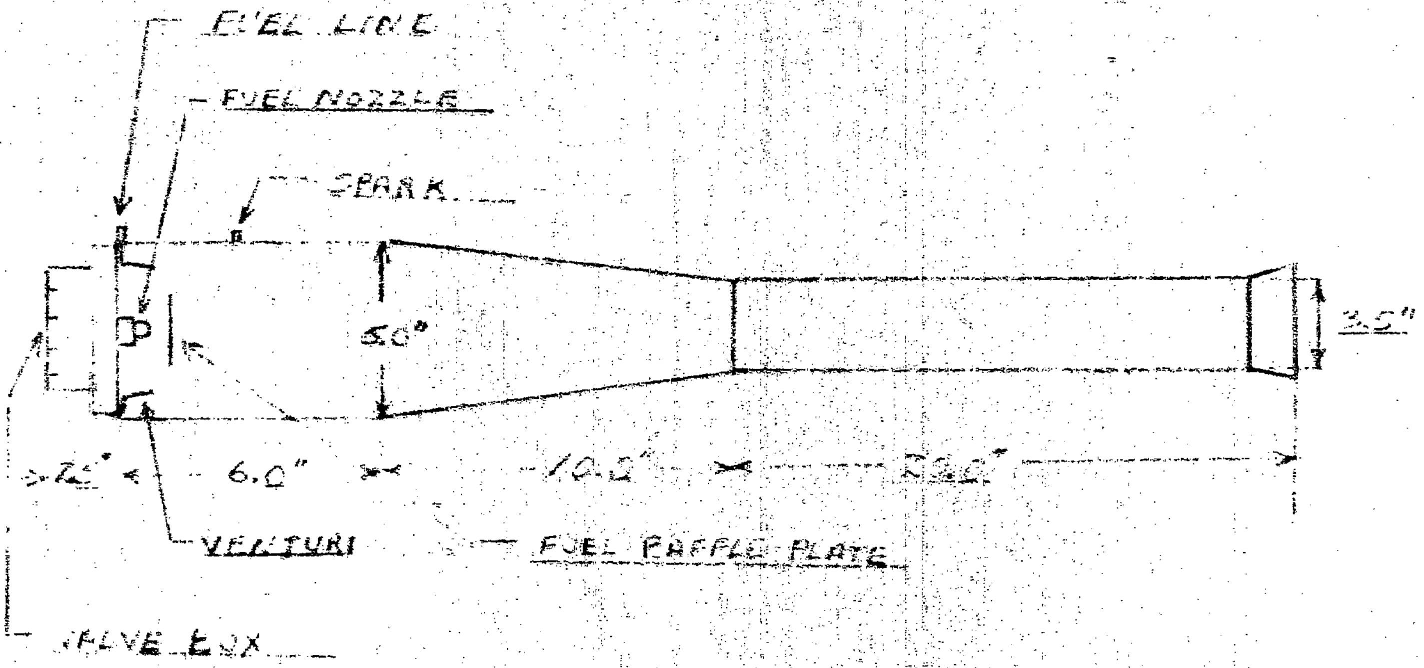


FIGURE 1

[illegible] AND THRUST [illegible]

FIGURE 2

SCHEMATIC DRAWING OF THE ENGINE



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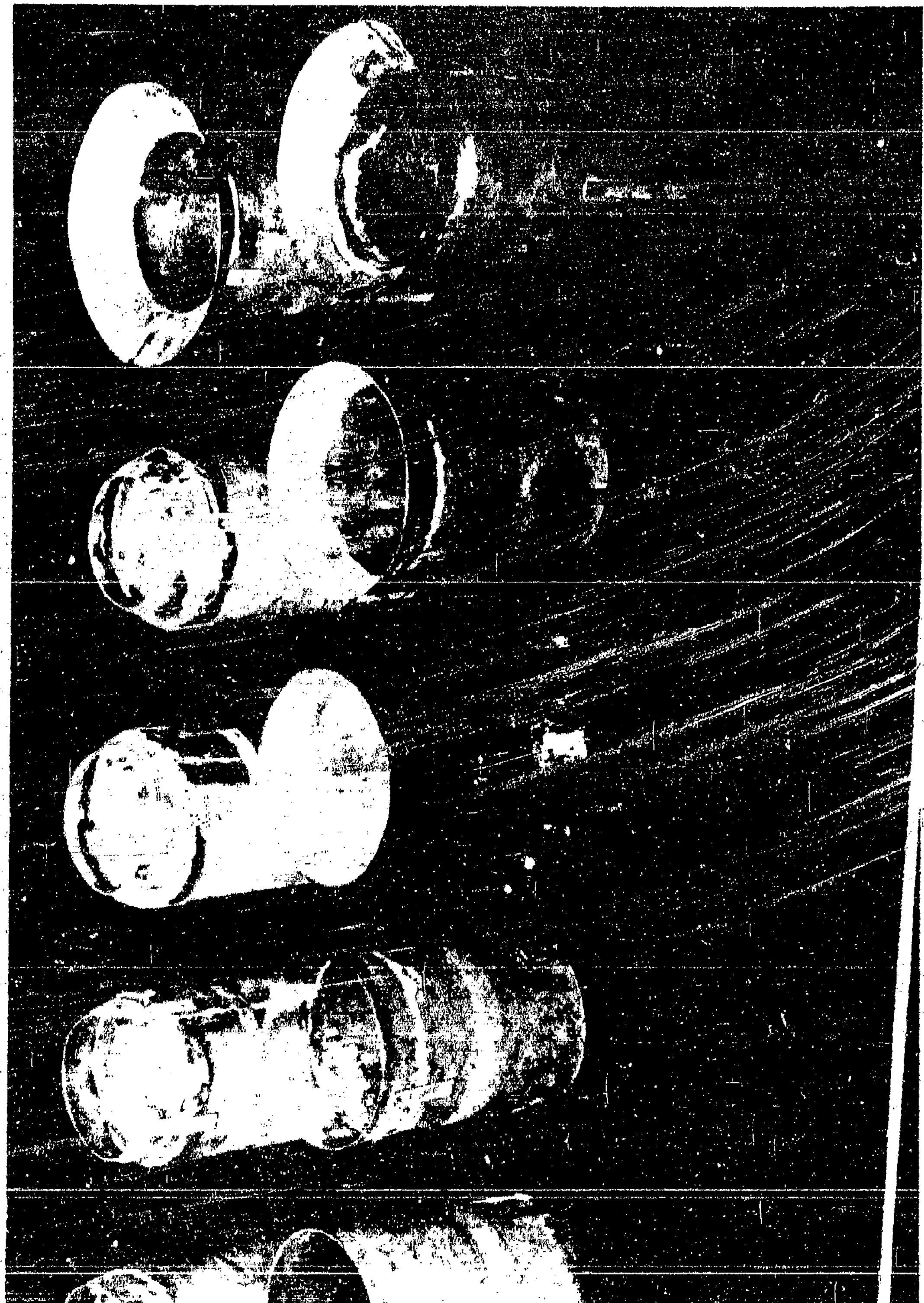


FIGURE 8
TAIL SECTIONS

FIGURE 4

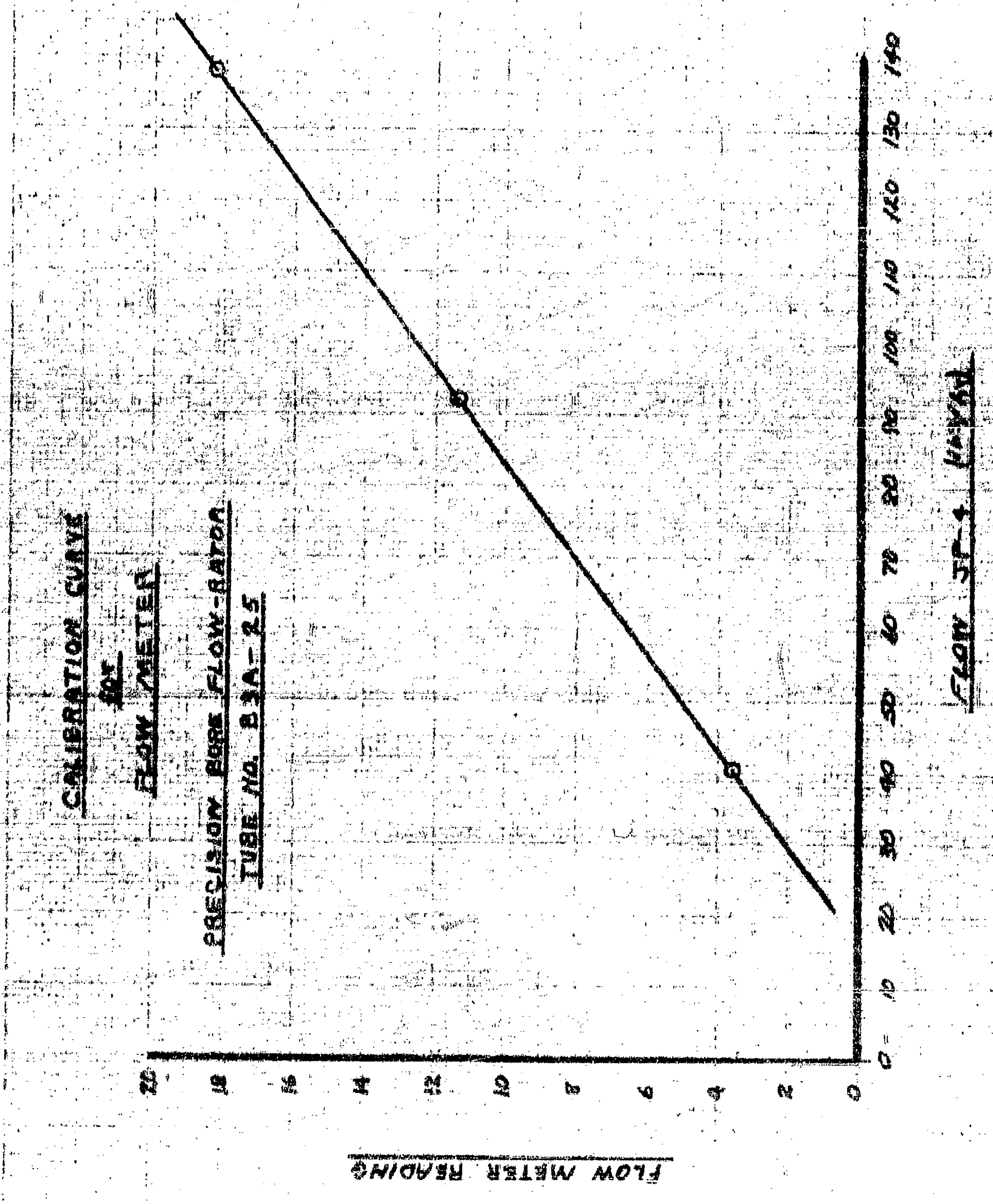

CALIBRATION CURVE
for
FLOW METER
PRECISION BORE FLOW-RATOR
TUBE NO. B3A-25
FLOW METER READING
FLOW JP-4
0
2
4
6
8
10
12
14
16
18
20
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140

FIGURE 5

FUEL NOZZLE AND BAFFLE PLATE

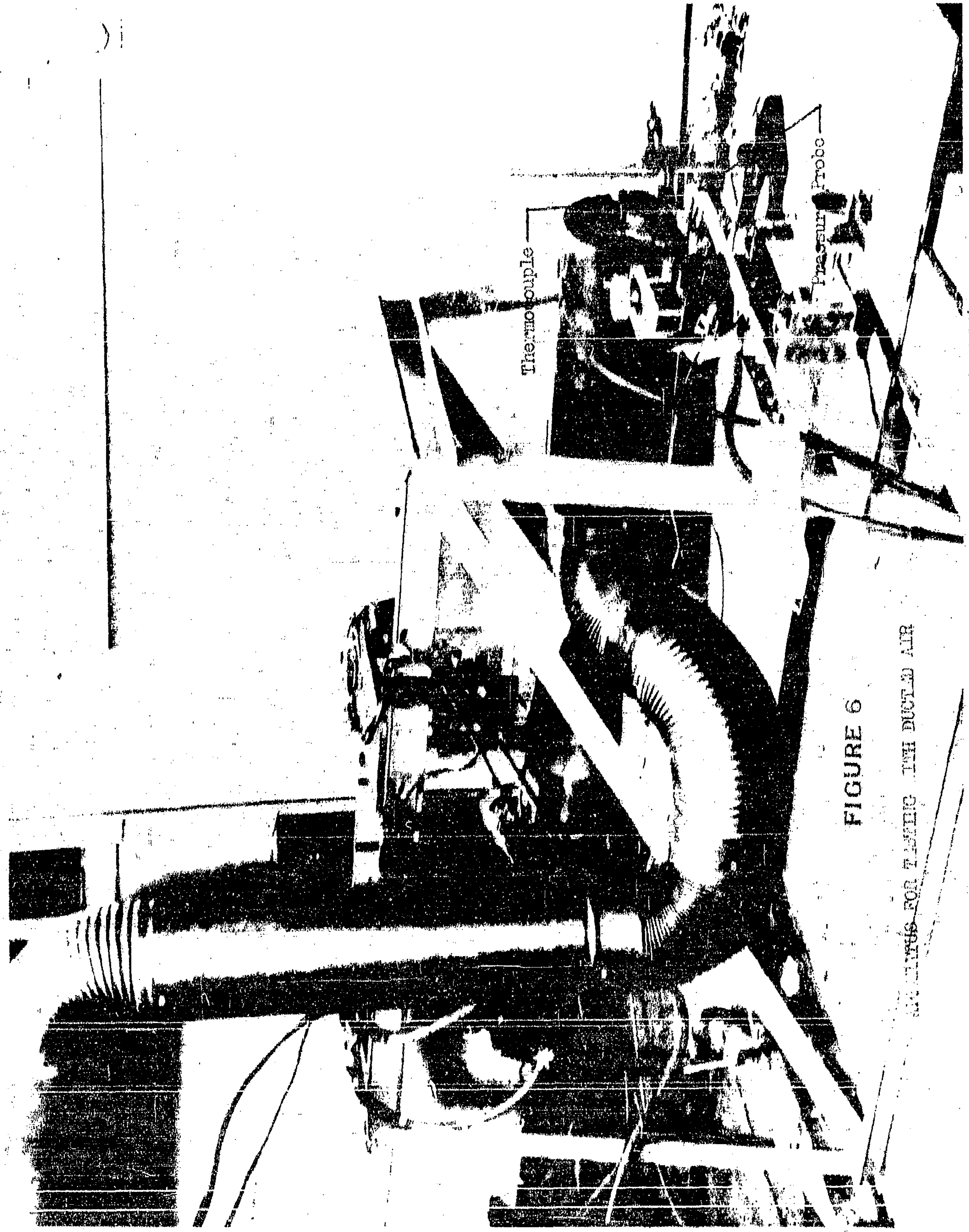


FIGURE 6

APPARATUS FOR TESTING THE DUCTED AIR

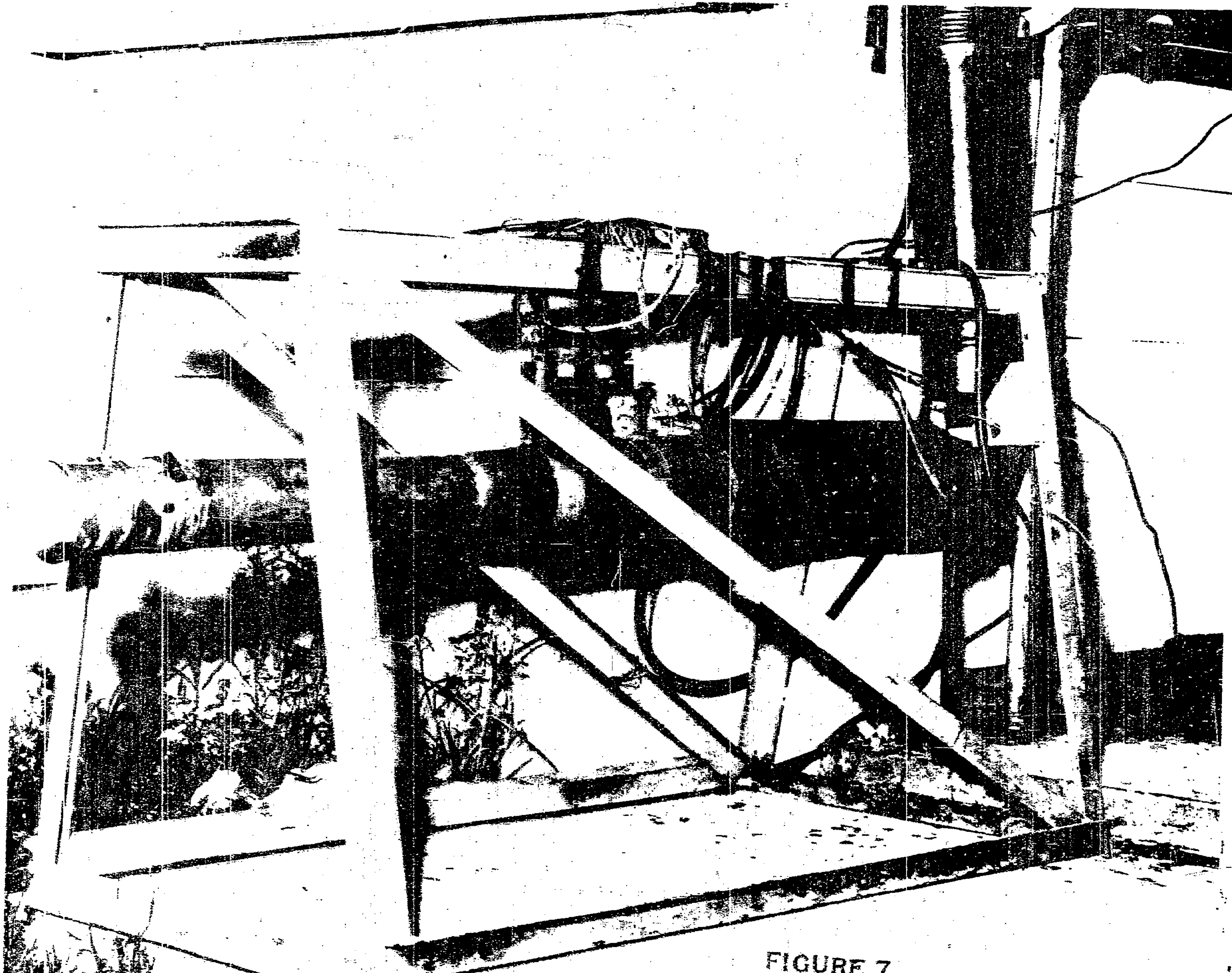
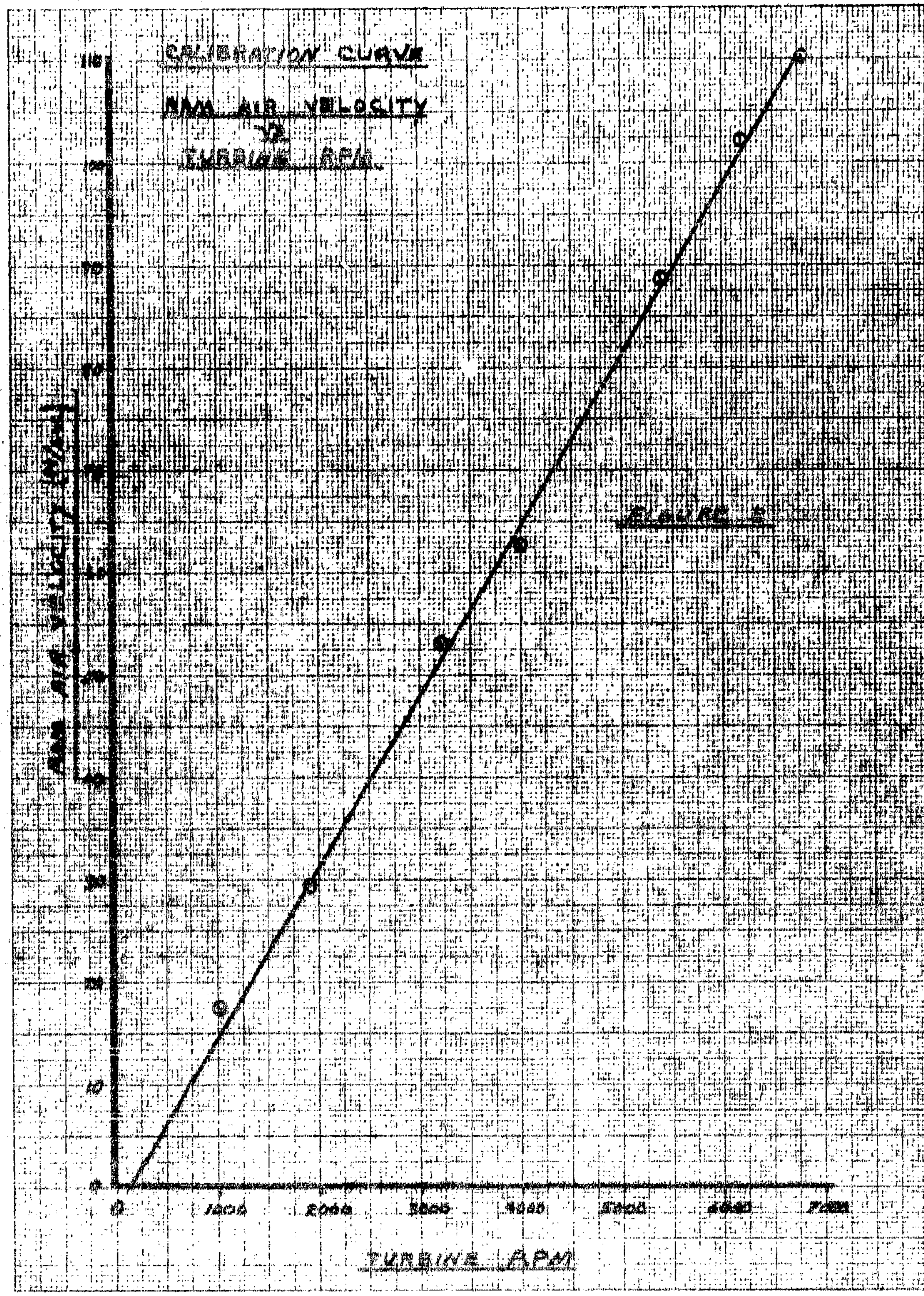


FIGURE 7

APPARATUS FOR TESTING WITH RAM AIR


CALIBRATION CURVE
AIR VELOCITY
VS
0
1000
2000
TURBINE RPM

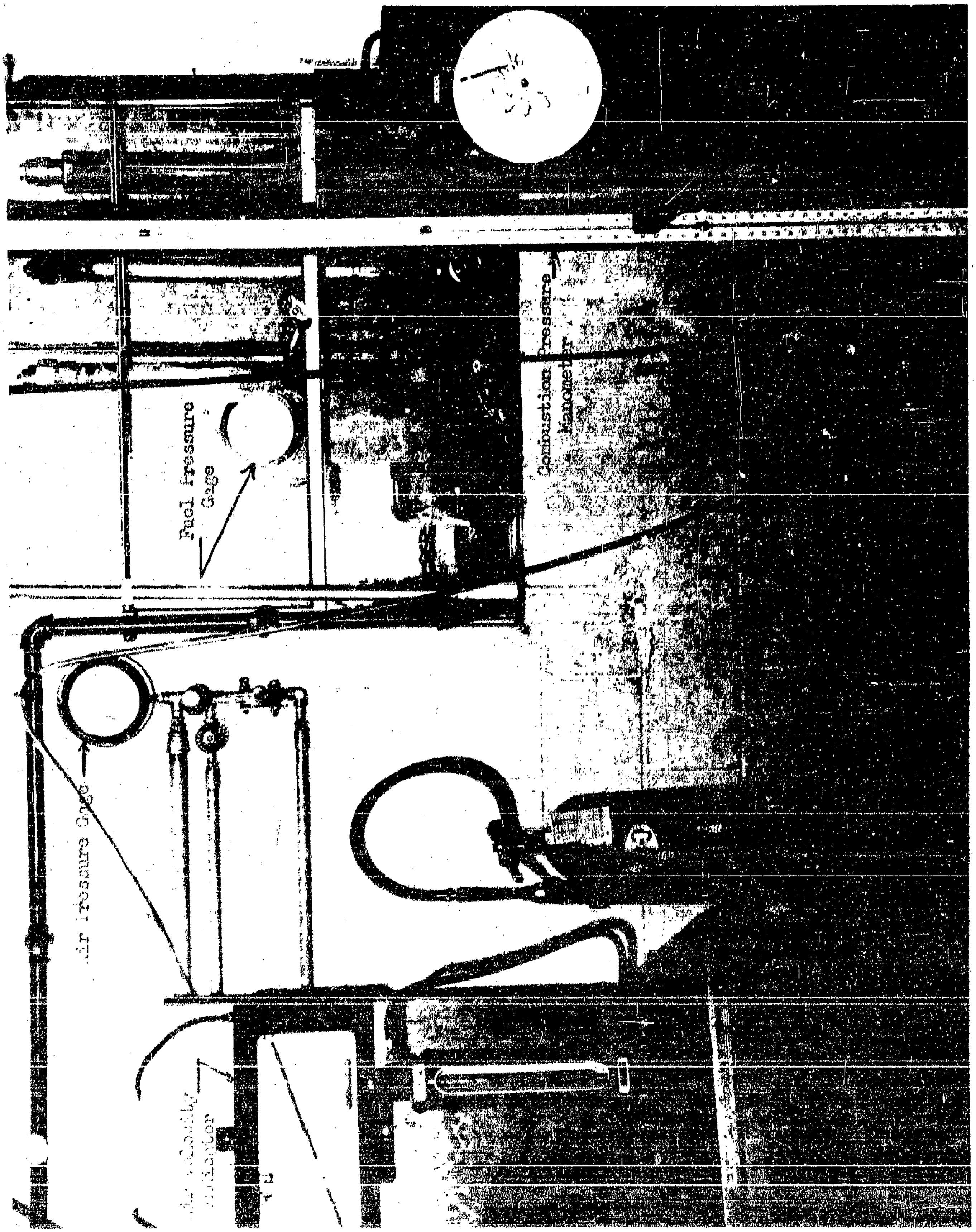


FIGURE 9

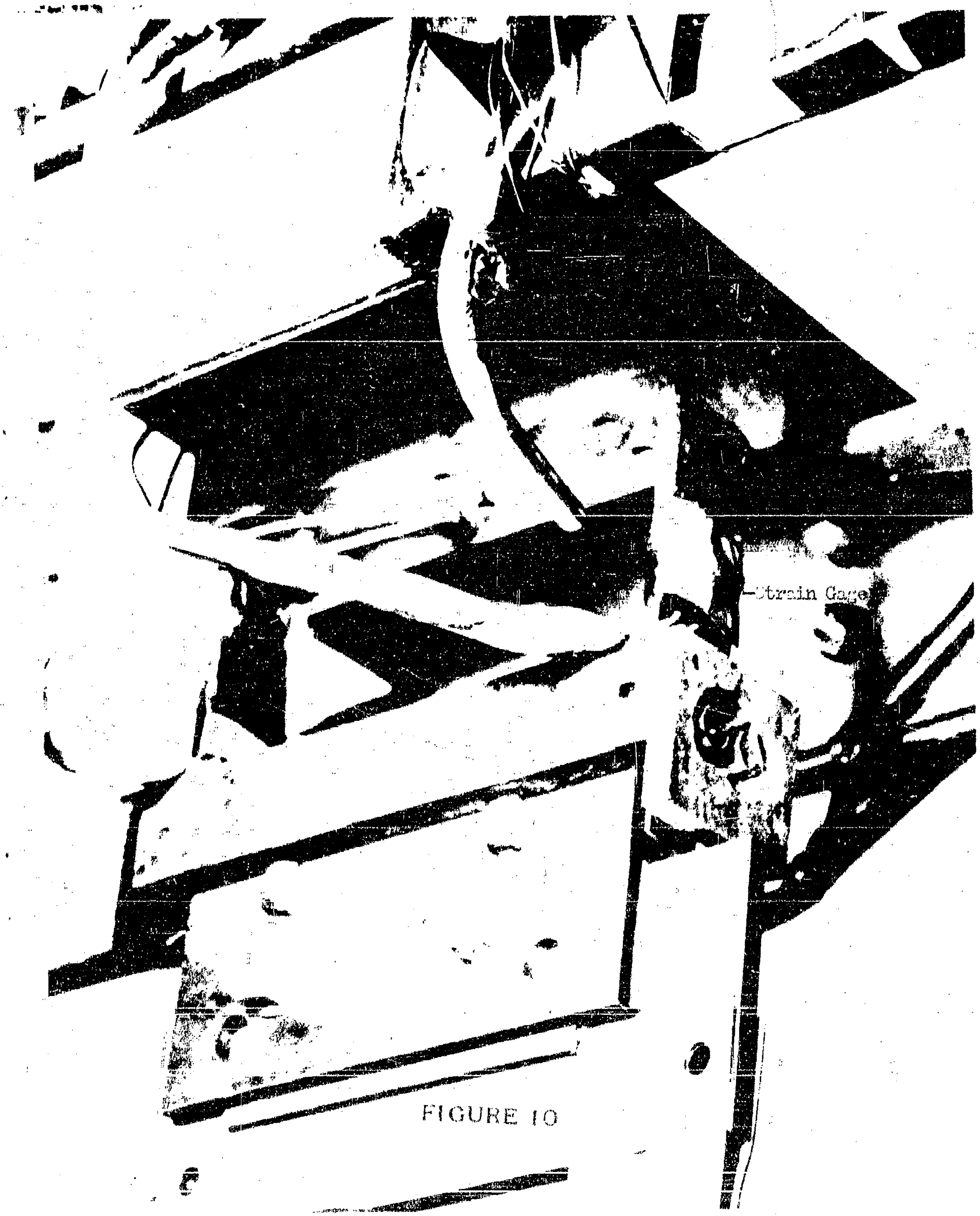


FIGURE 10

FIGURE 11

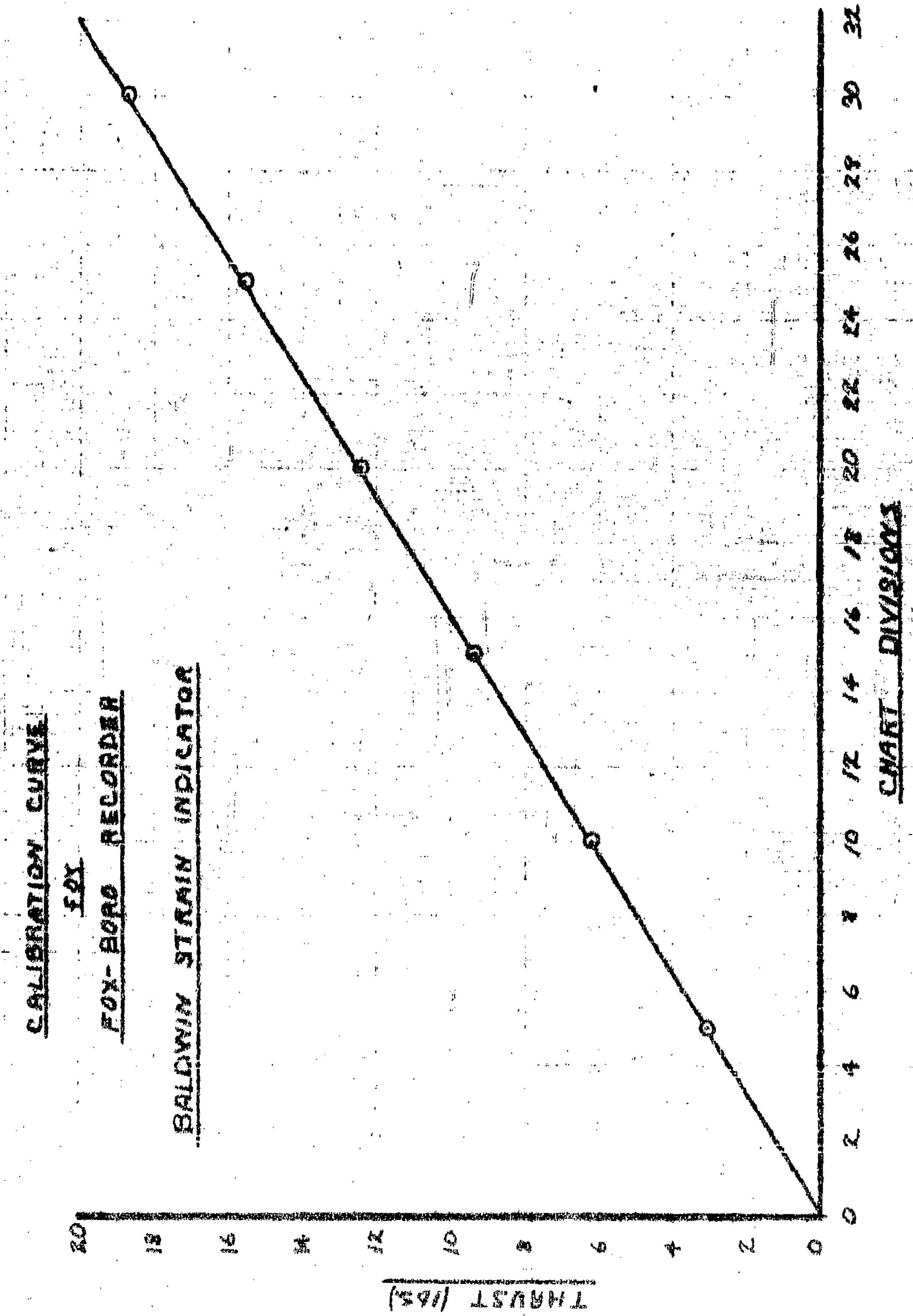

CALIBRATION CURVE
FOR
FOX-BORO RECORDER
BALDWIN STRAIN INDICATOR
CHART DIVISIONS
THRUST (lbs)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
0 2 4 6 8 10 12 14 16 18 20

FIGURE 12

FUEL FLOW VS COMBUSTION CHAMBER PRESSURE
FOR
VARIOUS TAIL ANGLES

AIR VELOCITY = 0

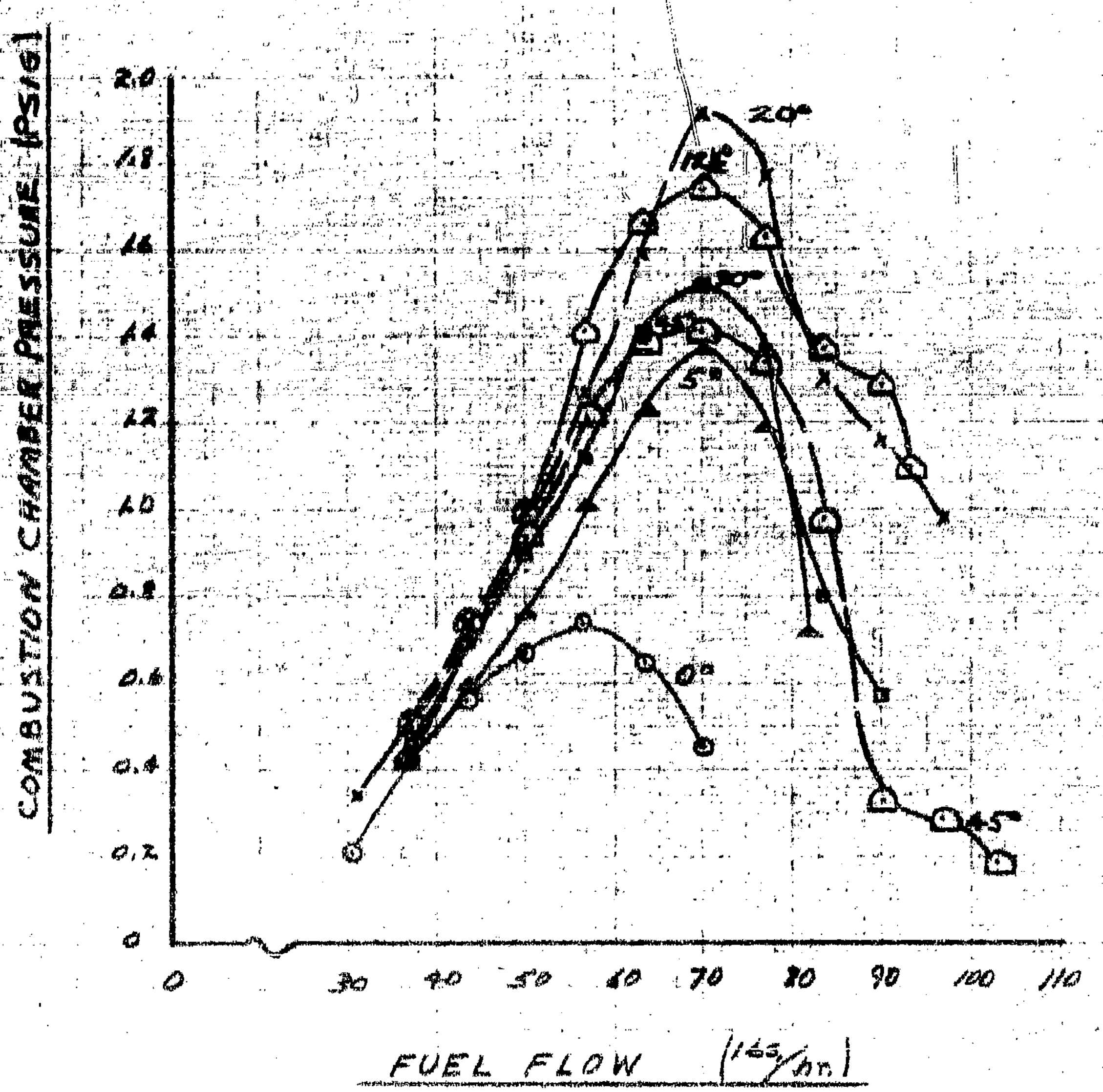


FIGURE 13

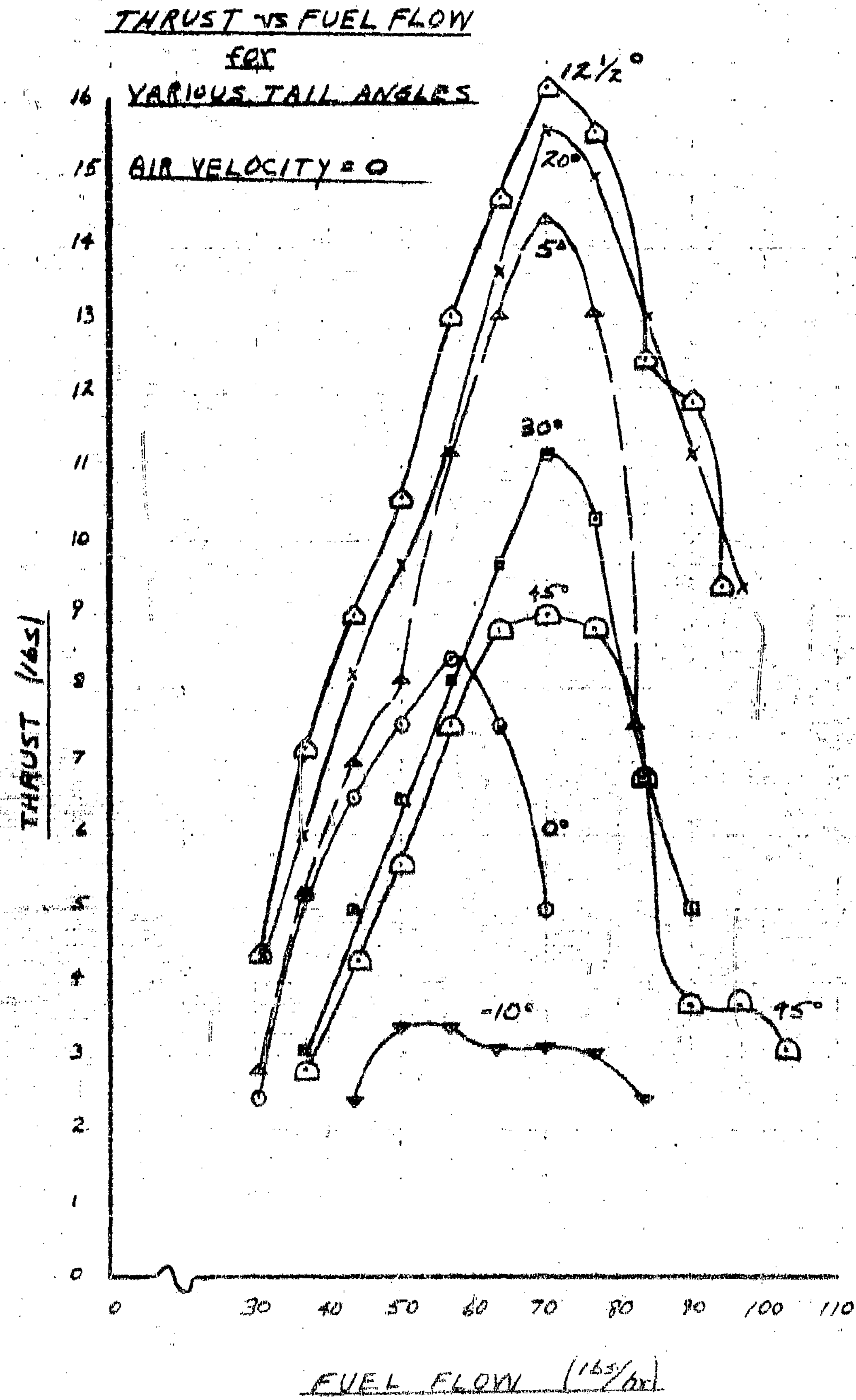

THRUST vs FUEL FLOW
for
VARIOUS TAIL ANGLES
AIR VELOCITY = 0
12½°
20°
5°
30°
45°
0°
-10°
45°
THRUST (lbs)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
0
30
40
50
60
70
80
90
100
110
FUEL FLOW (lbs/hr)

FIGURE 14

COMBUSTION CHAMBER PRESSURE VS THRUST
FOR
VARIOUS TAIL ANGLES

AIR VELOCITY = 0

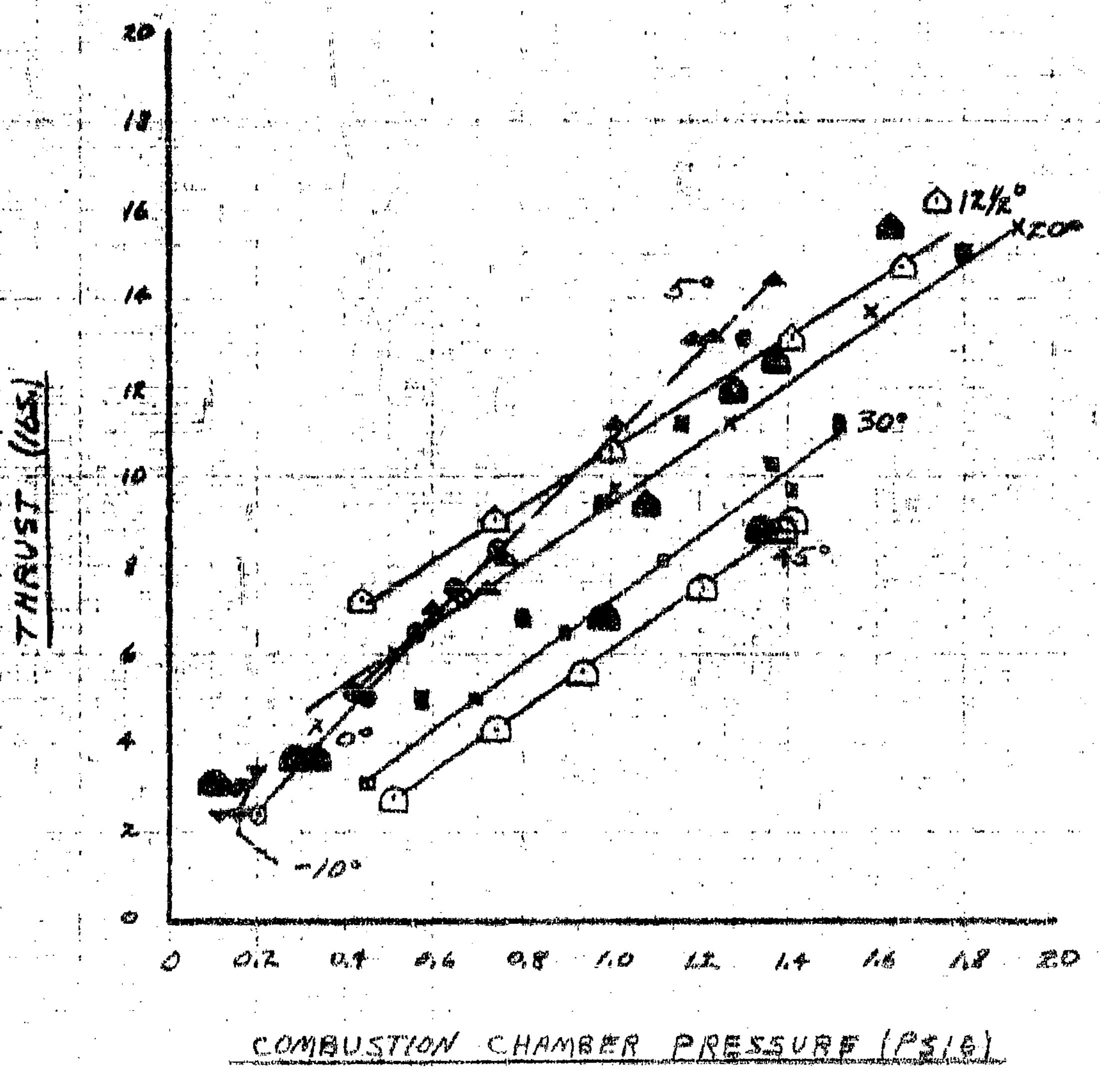


FIGURE 15

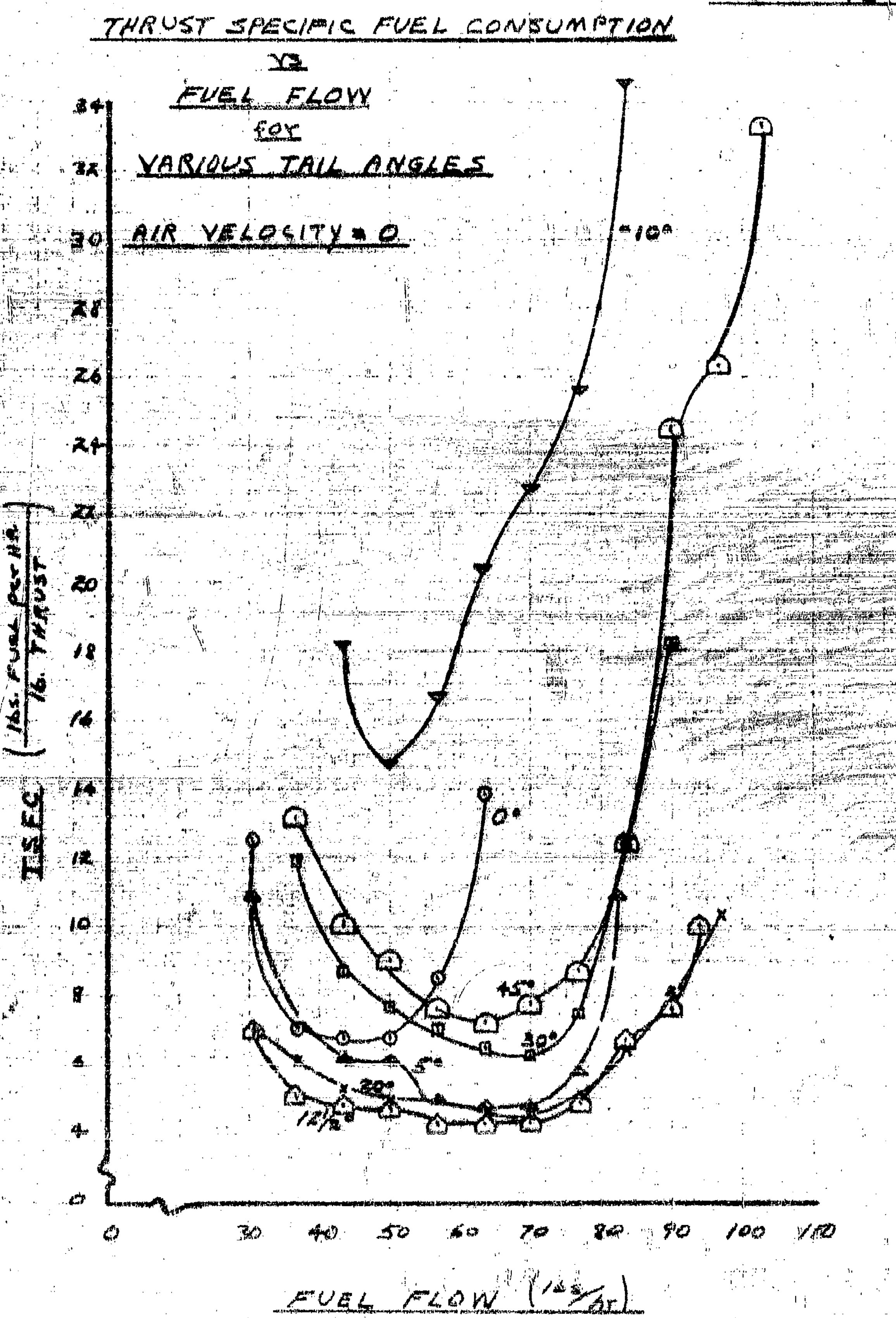

THRUST SPECIFIC FUEL CONSUMPTION
VS
FUEL FLOW
for
VARIOUS TAIL ANGLES
AIR VELOCITY = 0
TSFC (lbs. fuel per hr. / lb. thrust)
FUEL FLOW (lbs/hr)
-10°
0°
45°
30°
5°
20°
12½°
0
30
40
50
60
70
80
90
100
110
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34

FIGURE 16

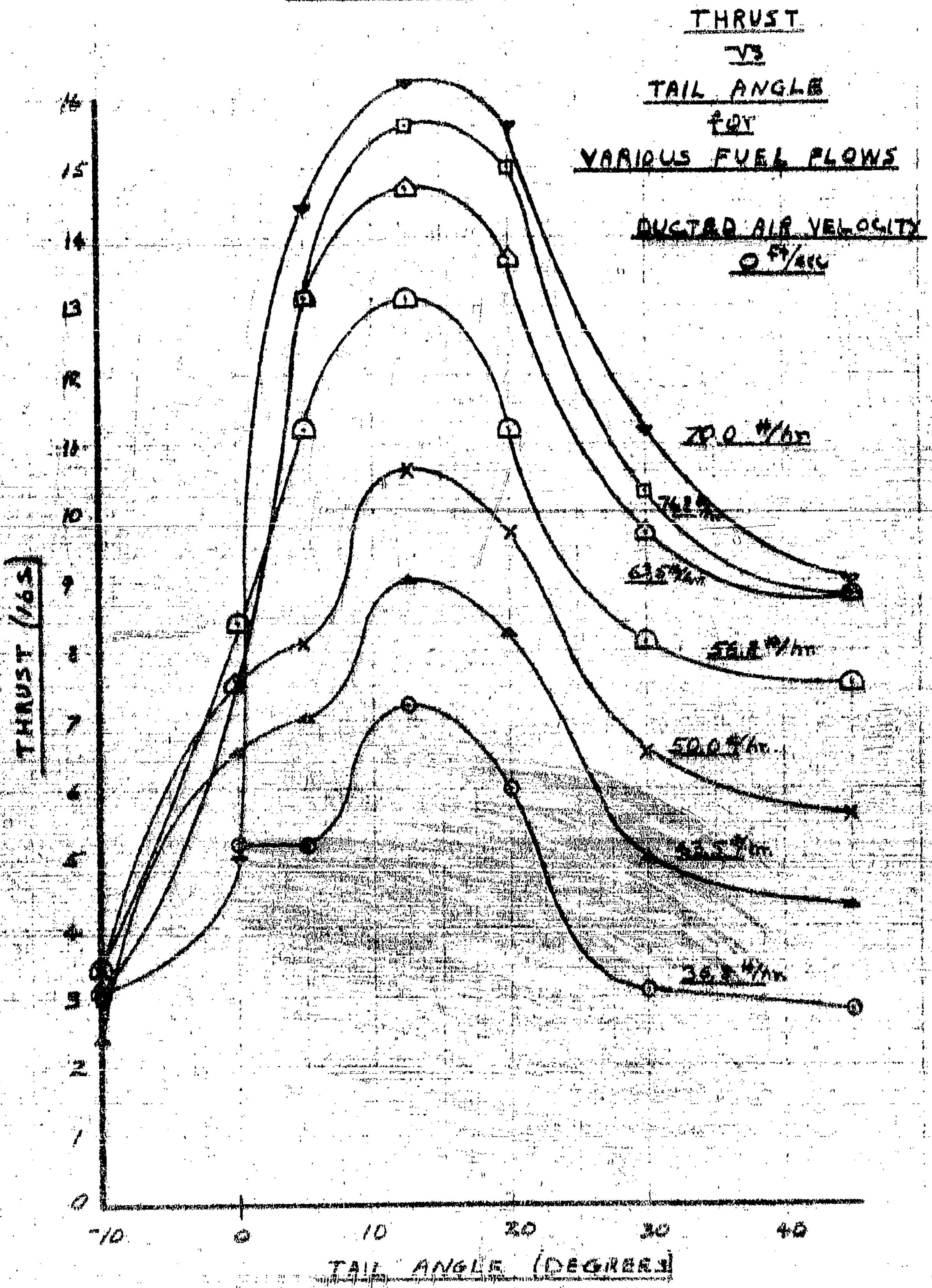
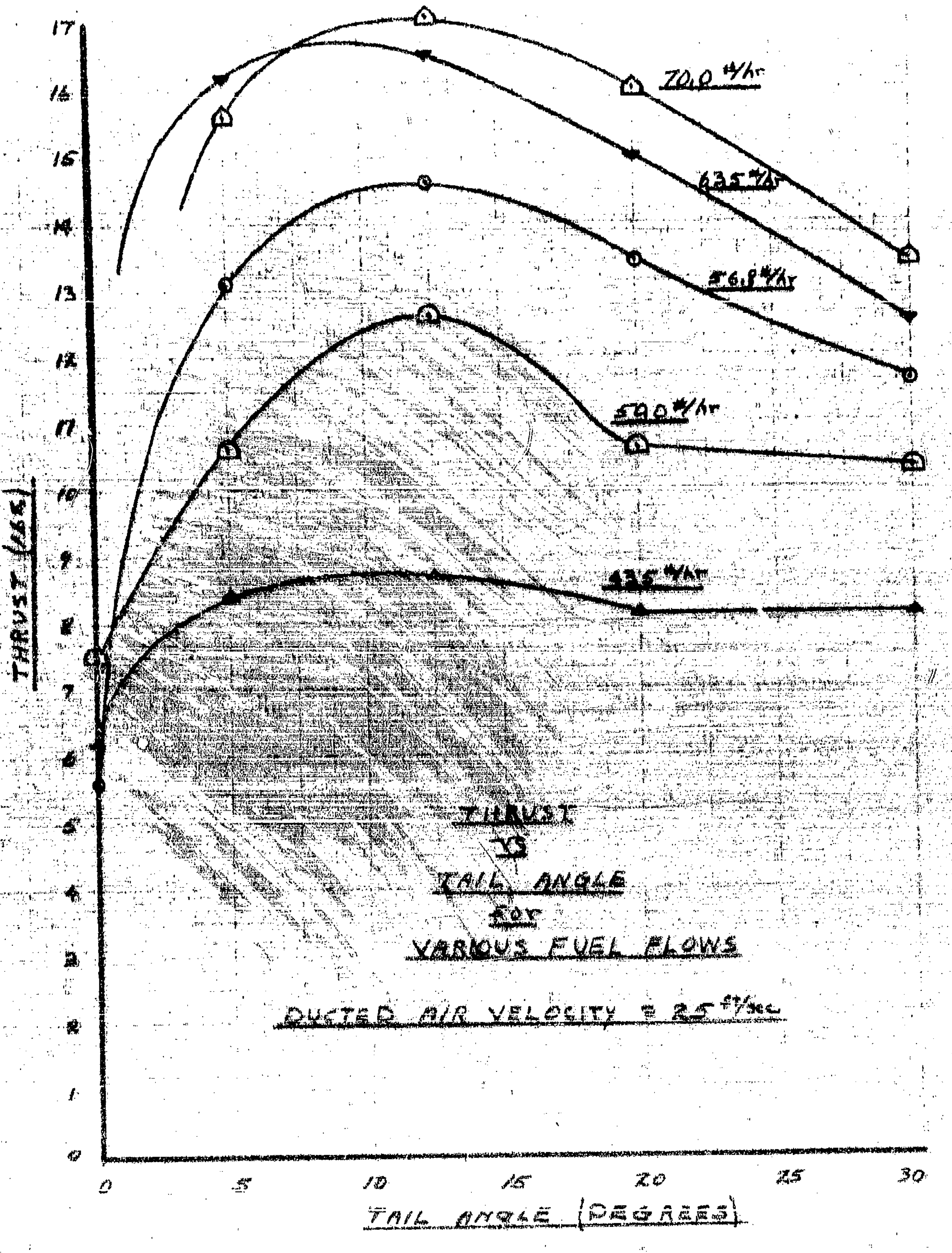

THRUST
VS
TAIL ANGLE
for
VARIOUS FUEL FLOWS
DUCTED AIR VELOCITY
0 ft/sec
70.0 #/hr
56.8 #/hr
50.0 #/hr
THRUST (lbs)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
-10
0
10
20
30
40
TAIL ANGLE (DEGREES)

FIGURE 17



17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
THRUST (LBS)
70.0 #/hr
63.5 #/hr
56.8 #/hr
59.0 #/hr
43.5 #/hr
THRUST
VS
TAIL ANGLE
FOR
VARIOUS FUEL FLOWS
DUCTED AIR VELOCITY = 25 ft/sec
0
5
10
15
20
25
30
TAIL ANGLE (DEGREES)

FIGURE 18

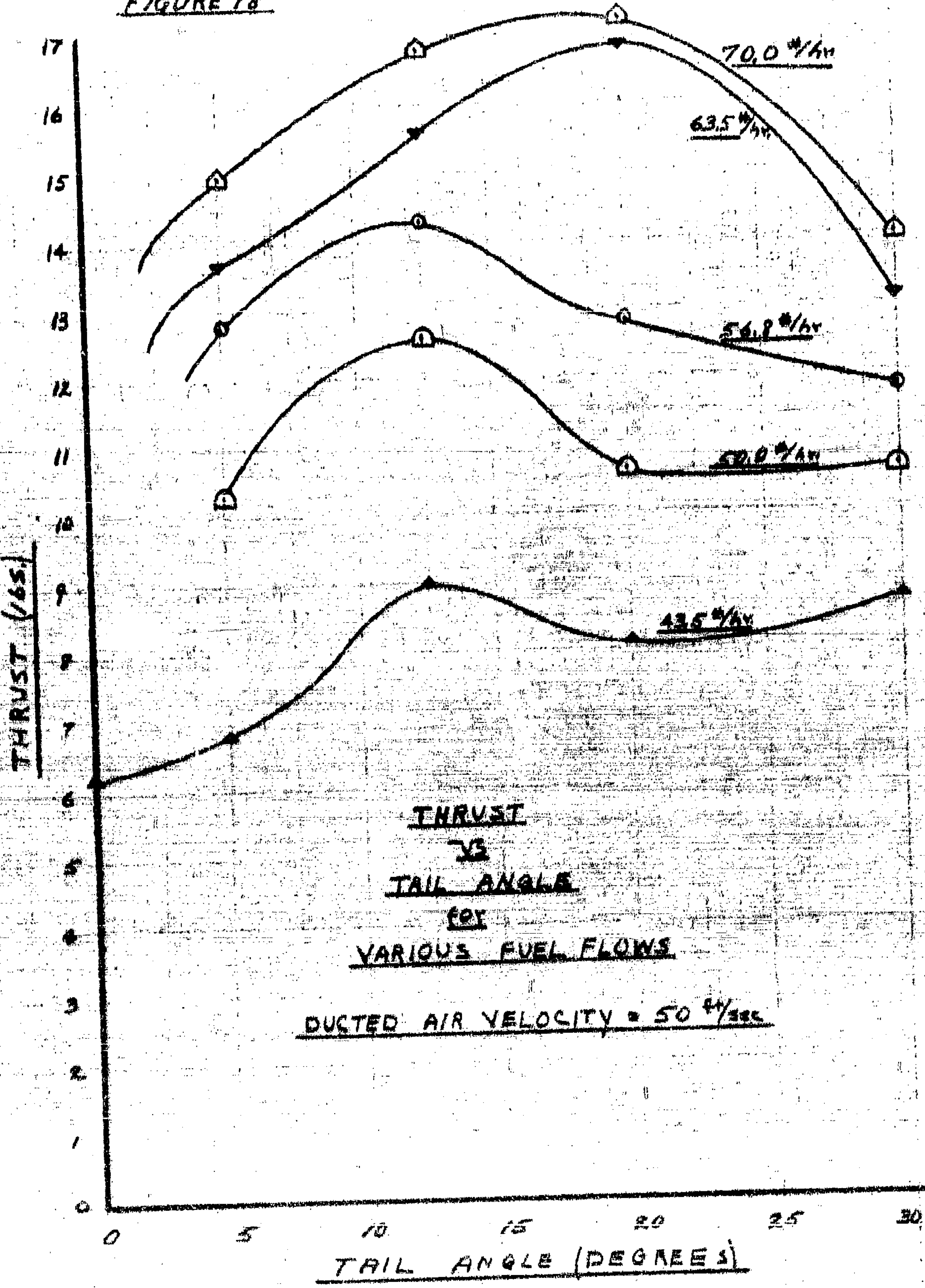

70.0 #/hr
63.5 #/hr
56.8 #/hr
50.0 #/hr
43.5 #/hr
THRUST (lbs.)
TAIL ANGLE (DEGREES)
THRUST
VS
TAIL ANGLE
FOR
VARIOUS FUEL FLOWS
DUCTED AIR VELOCITY = 50 ft/sec
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
0
5
10
15
20
25
30

FIGURE 19

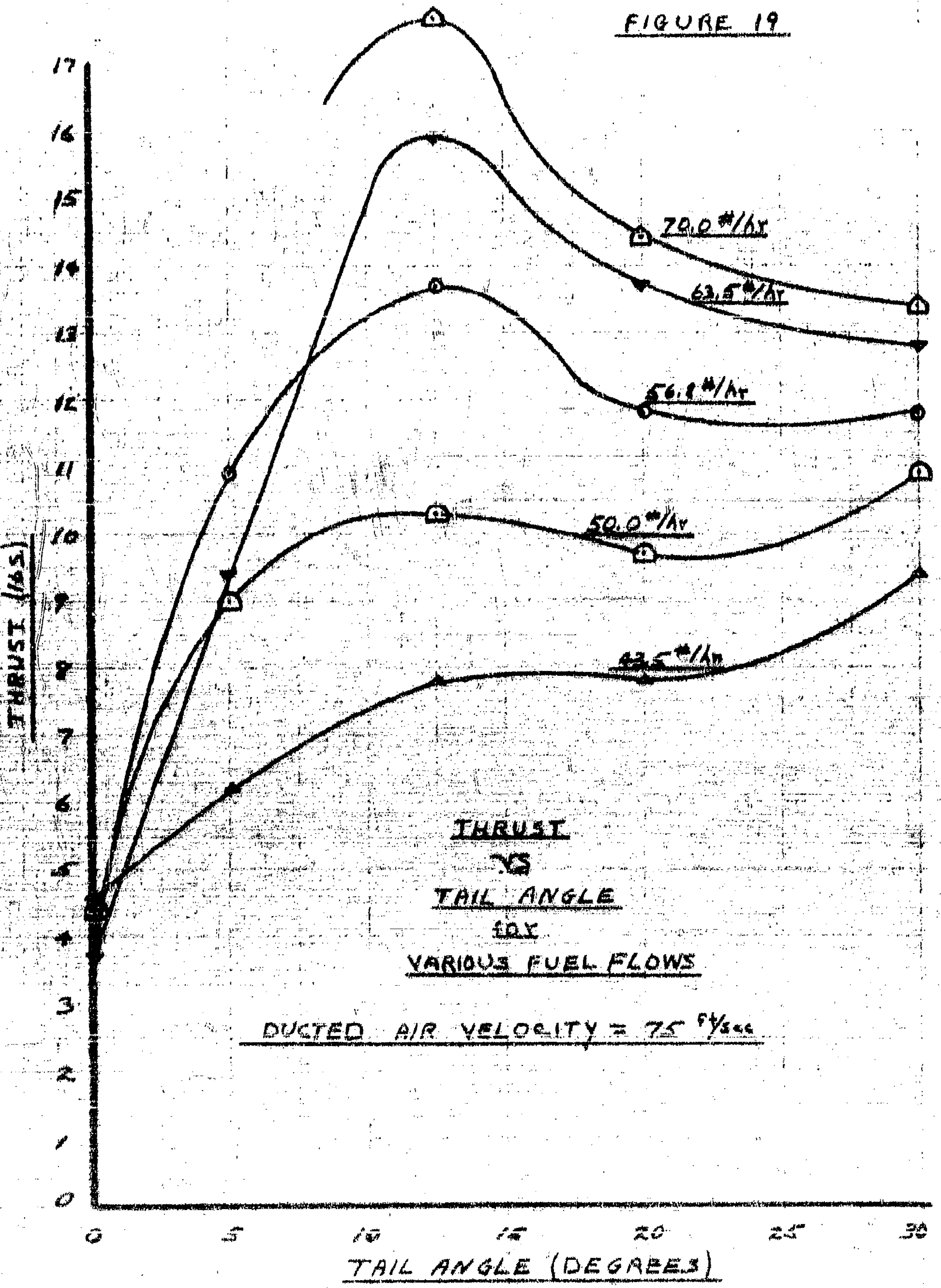

70.0 #/hr
63.5 #/hr
56.1 #/hr
50.0 #/hr
43.5 #/hr
THRUST (lbs)
THRUST
VS
TAIL ANGLE
for
VARIOUS FUEL FLOWS
DUCTED AIR VELOCITY = 75 ft/sec
TAIL ANGLE (DEGREES)
0
5
10
15
20
25
30
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

FIGURE 20

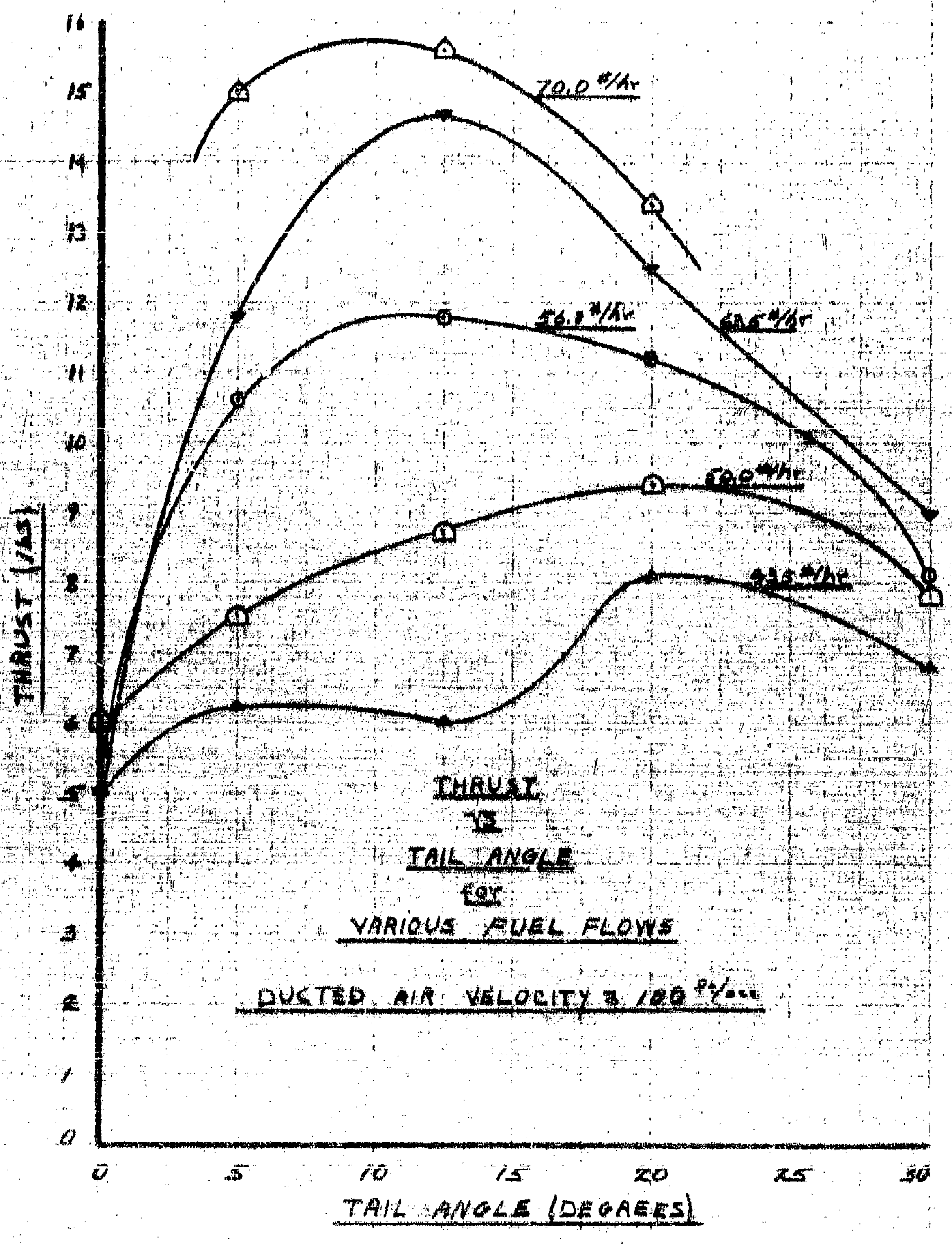

70.0 #/hr
56.1 #/hr
63.5 #/hr
50.0 #/hr
43.5 #/hr
THRUST (LBS)
TAIL ANGLE (DEGREES)
0
5
10
15
20
25
30
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
THRUST
vs
TAIL ANGLE
for
VARIOUS FUEL FLOWS
DUCTED AIR VELOCITY = 100 ft/sec

FIGURE 21

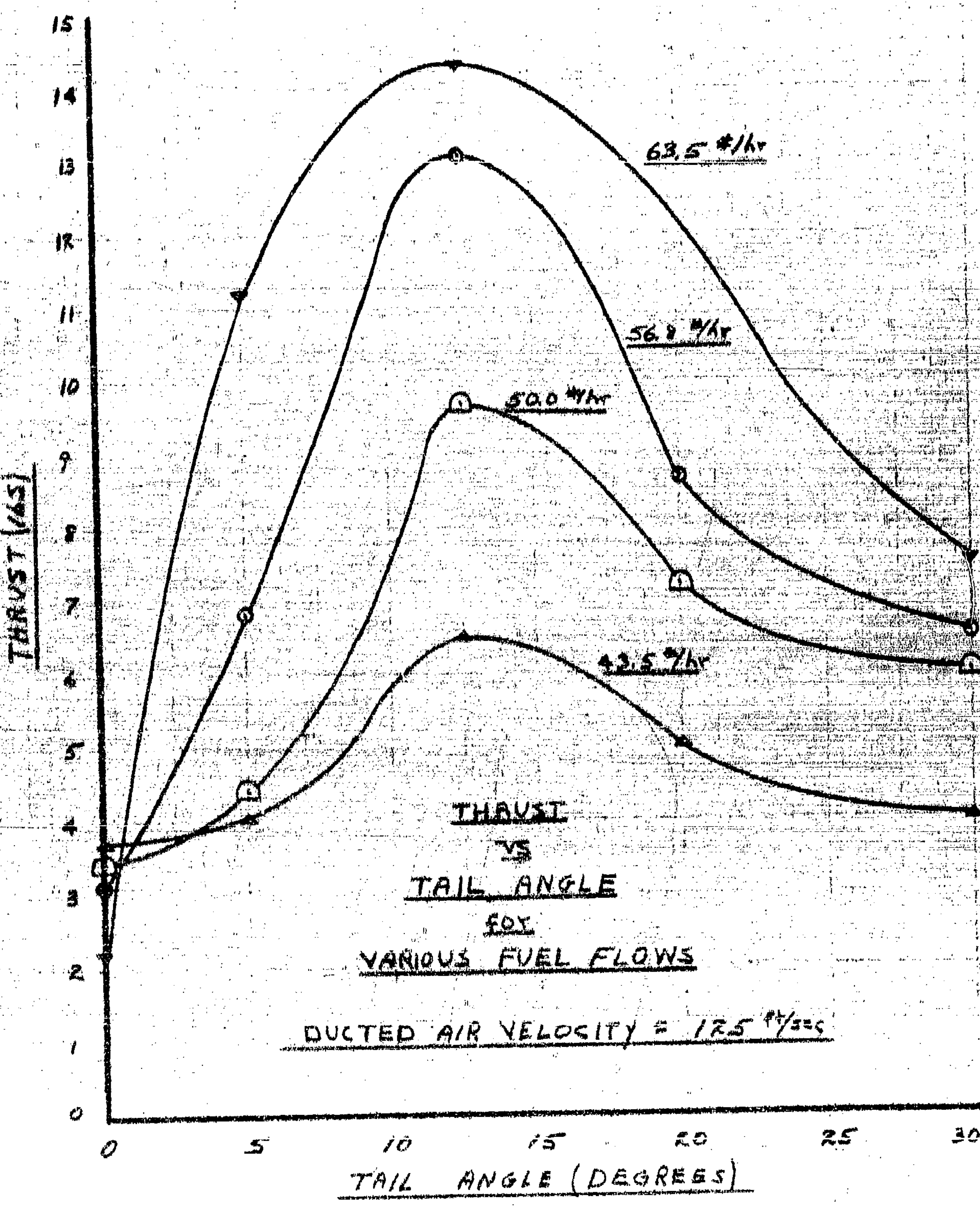

THRUST (lbs)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
63.5 #/hr
56.8 #/hr
50.0 #/hr
43.5 #/hr
THRUST
VS
TAIL ANGLE
FOR
VARIOUS FUEL FLOWS
DUCTED AIR VELOCITY = 12.5 ft/sec
0
5
10
15
20
25
30
TAIL ANGLE (DEGREES)

FIGURE 22

THRUST SPECIFIC FUEL CONSUMPTION VS FUEL FLOW

FOR VARIOUS DUCTED AIR VELOCITIES

0° TAIL ANGLE

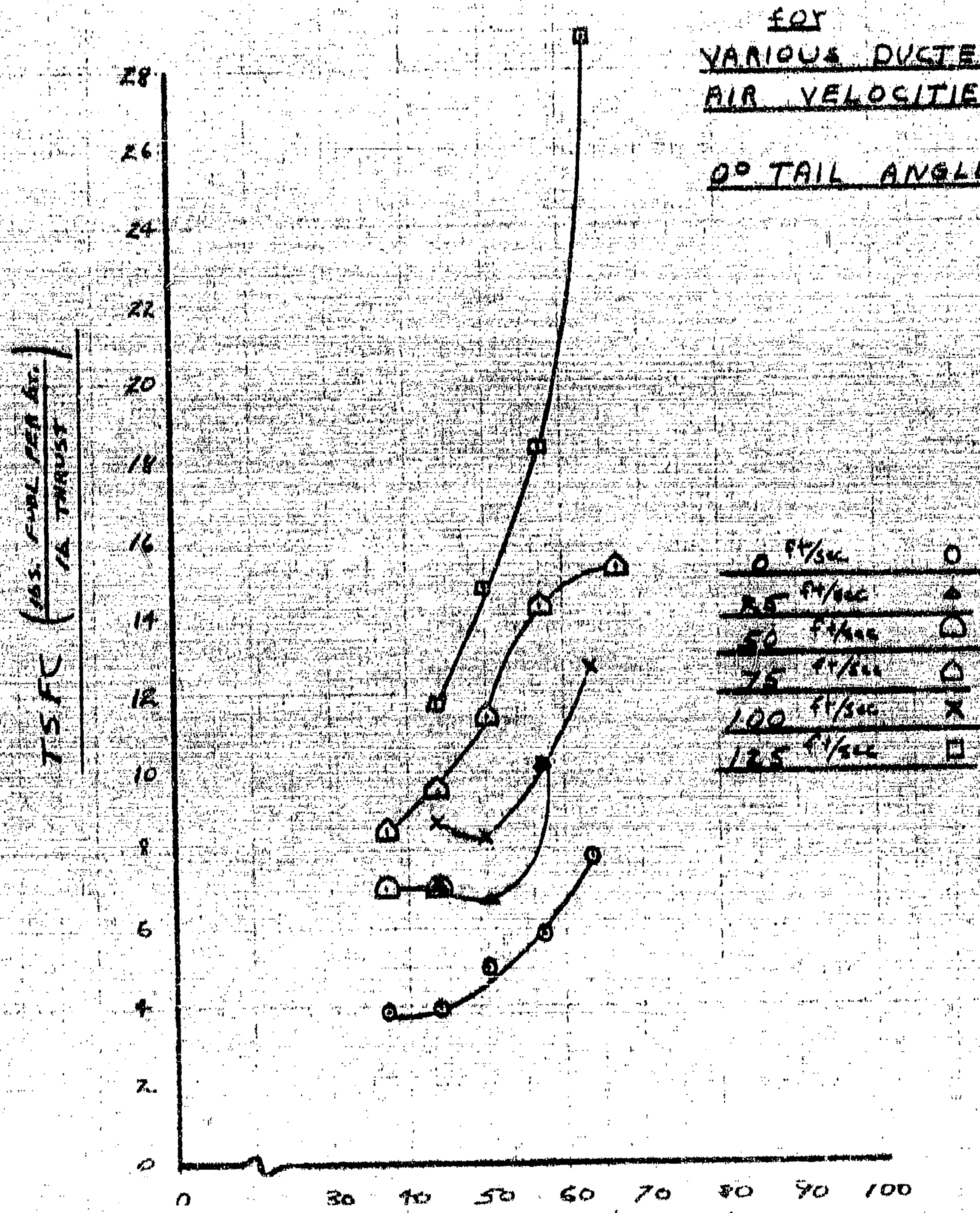


FIGURE 23

THRUST SPECIFIC FUEL CONSUMPTION

VS

FUEL FLOW

FOR

VARIOUS DUCTED AIR VELOCITIES

5° TAIL ANGLE

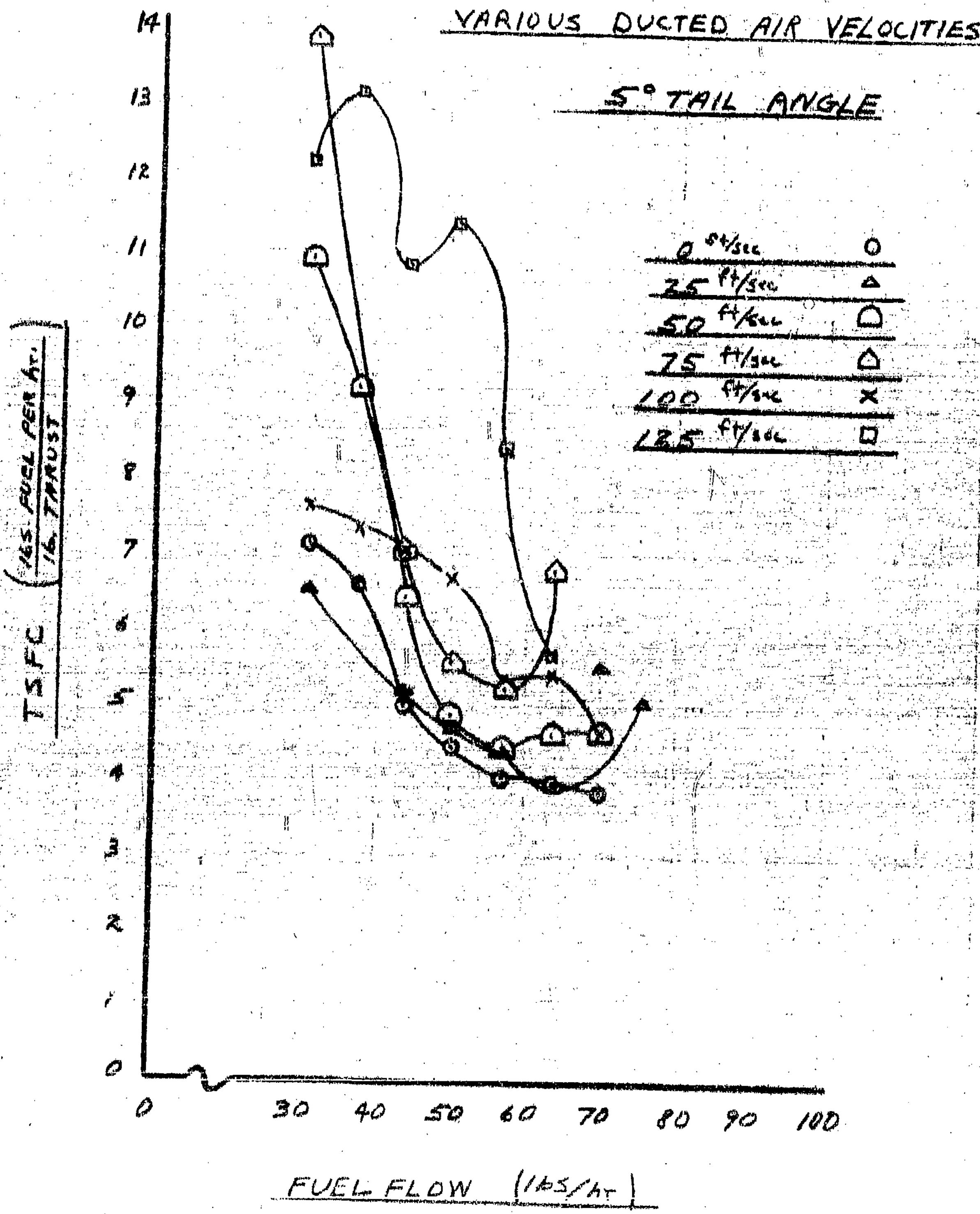


FIGURE 24

THRUST SPECIFIC FUEL CONSUMPTION
VS
FUEL FLOW
for
VARIOUS DUCTED AIR VELOCITIES

12½° TAIL ANGLE

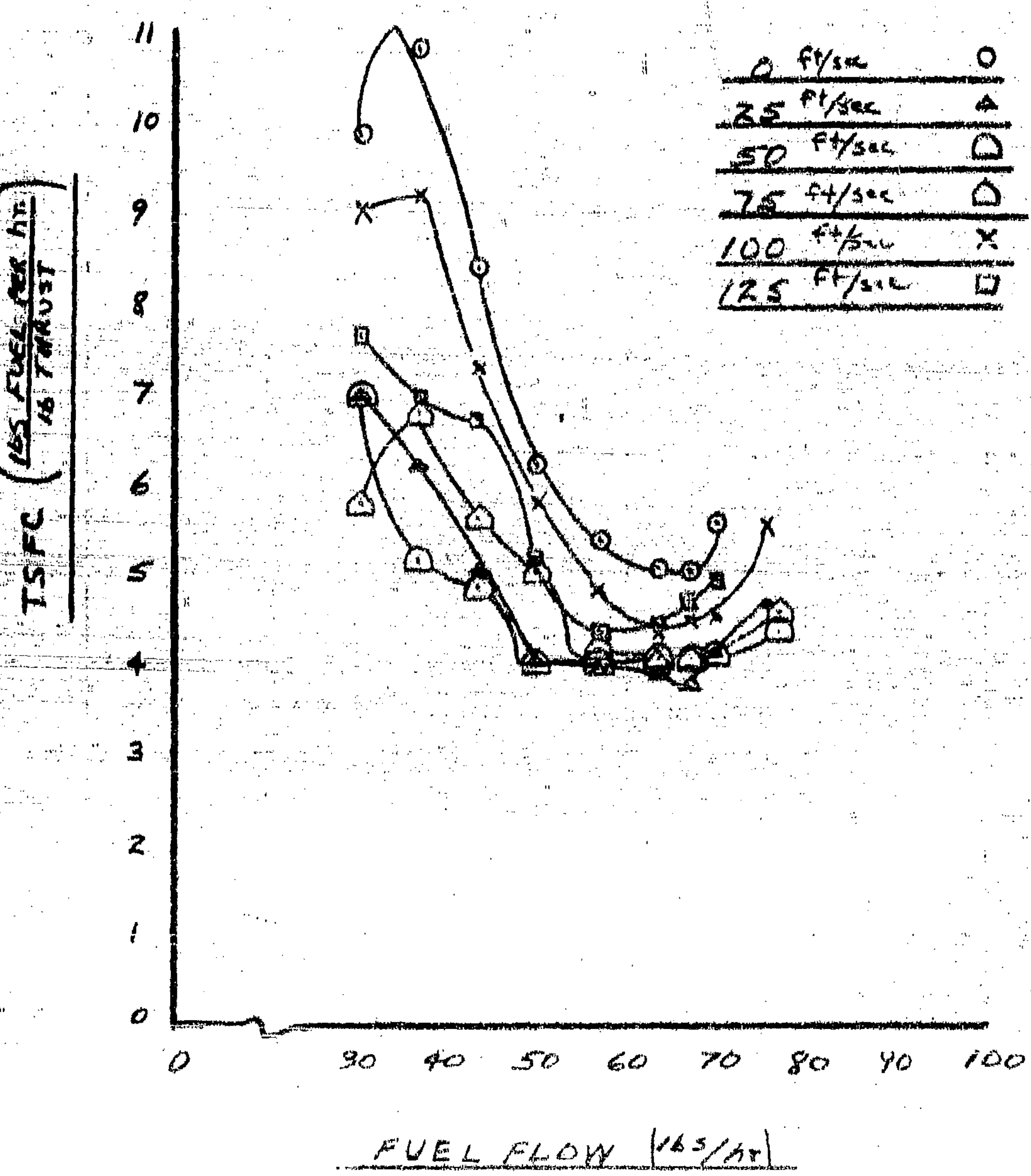


FIGURE 25

THRUST SPECIFIC FUEL CONSUMPTION VS FUEL FLOW FOR VARIOUS DUCTED AIR VELOCITIES

20° TAIL ANGLE

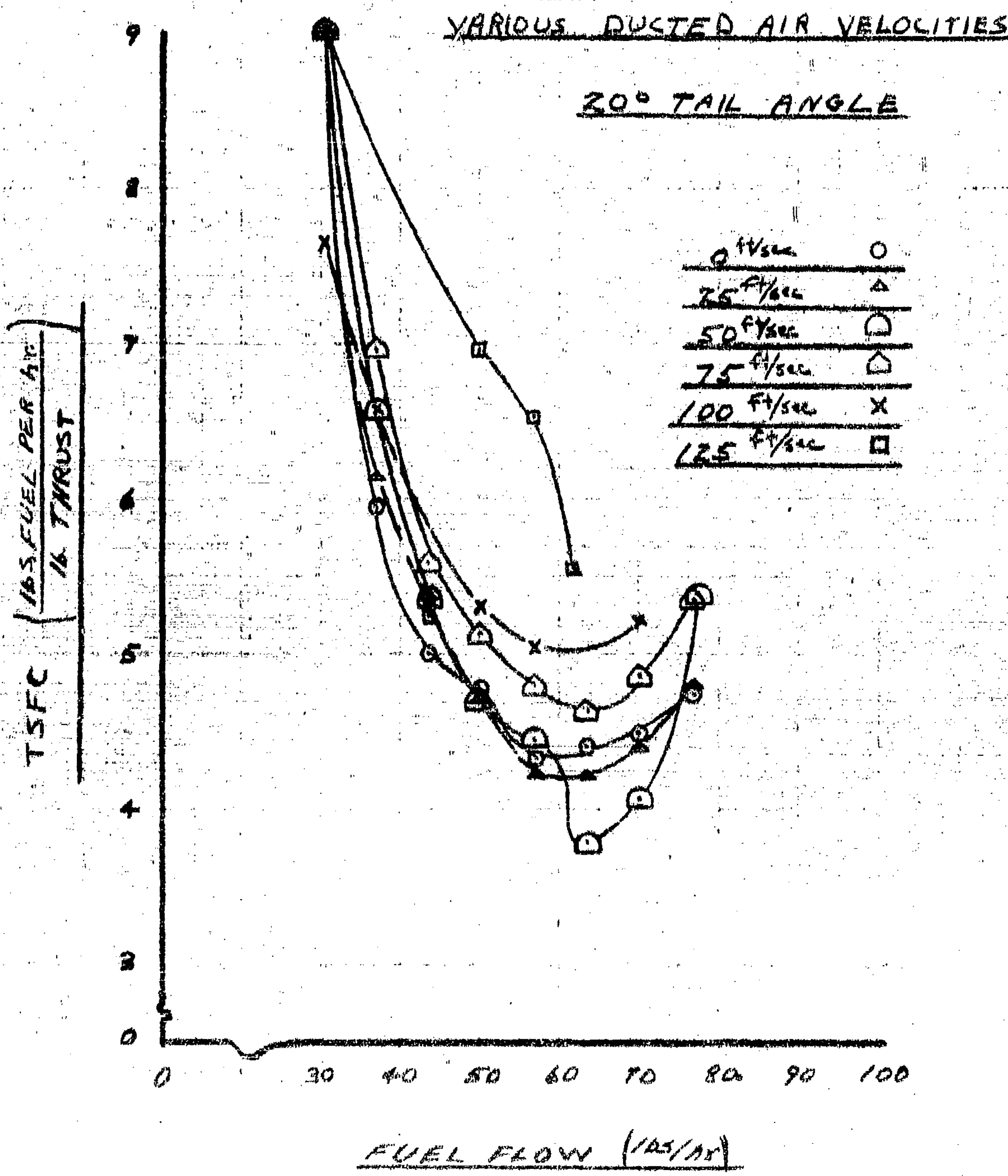


FIGURE 26

THRUST SPECIFIC FUEL CONSUMPTION

VS

FUEL FLOW

for

VARIOUS DUCTED AIR VELOCITIES

30° TAIL ANGLE

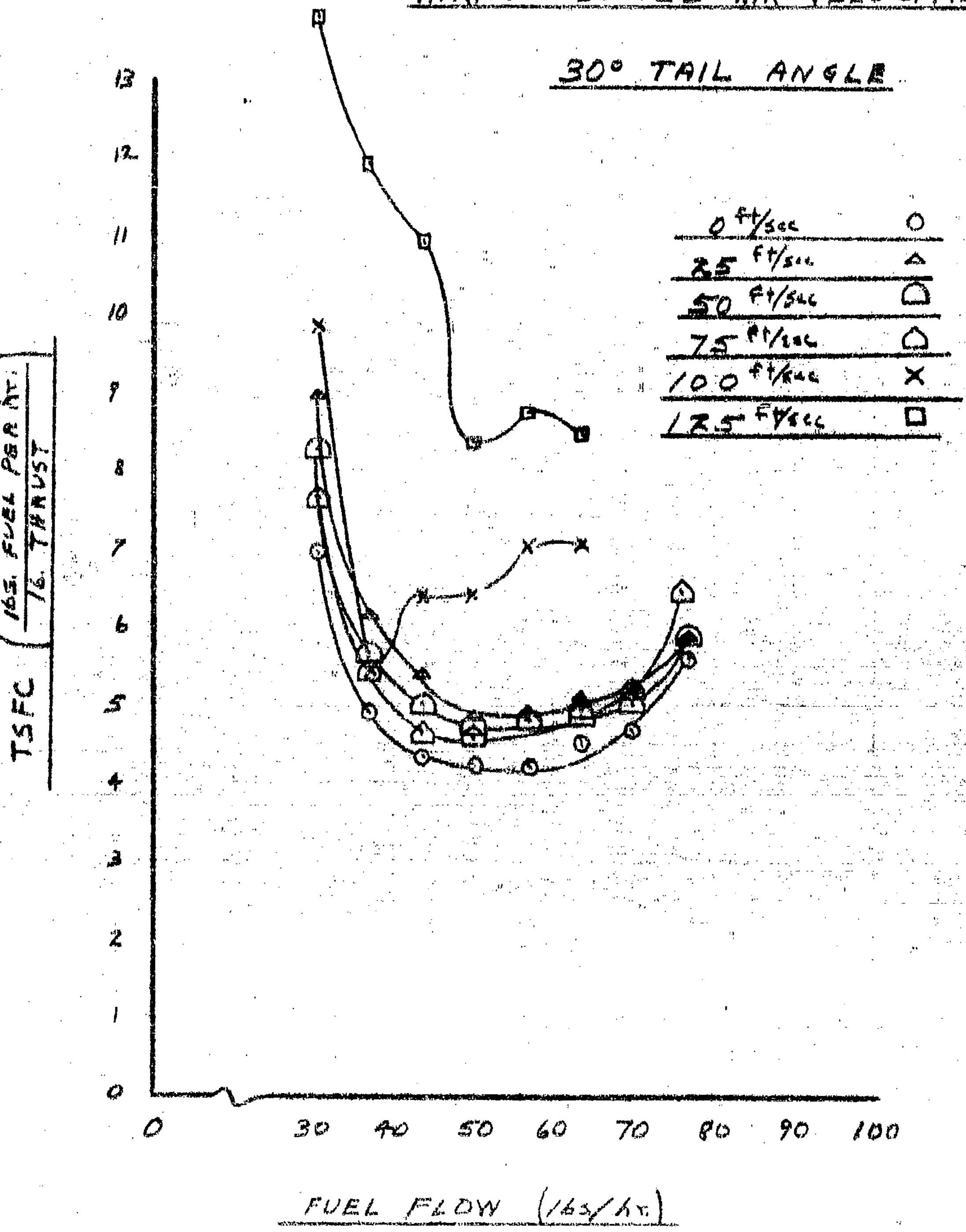


FIGURE 27

THRUST VS FUEL FLOW
for
VARIOUS DUCTED AIR VELOCITIES

0° TAIL ANGLE

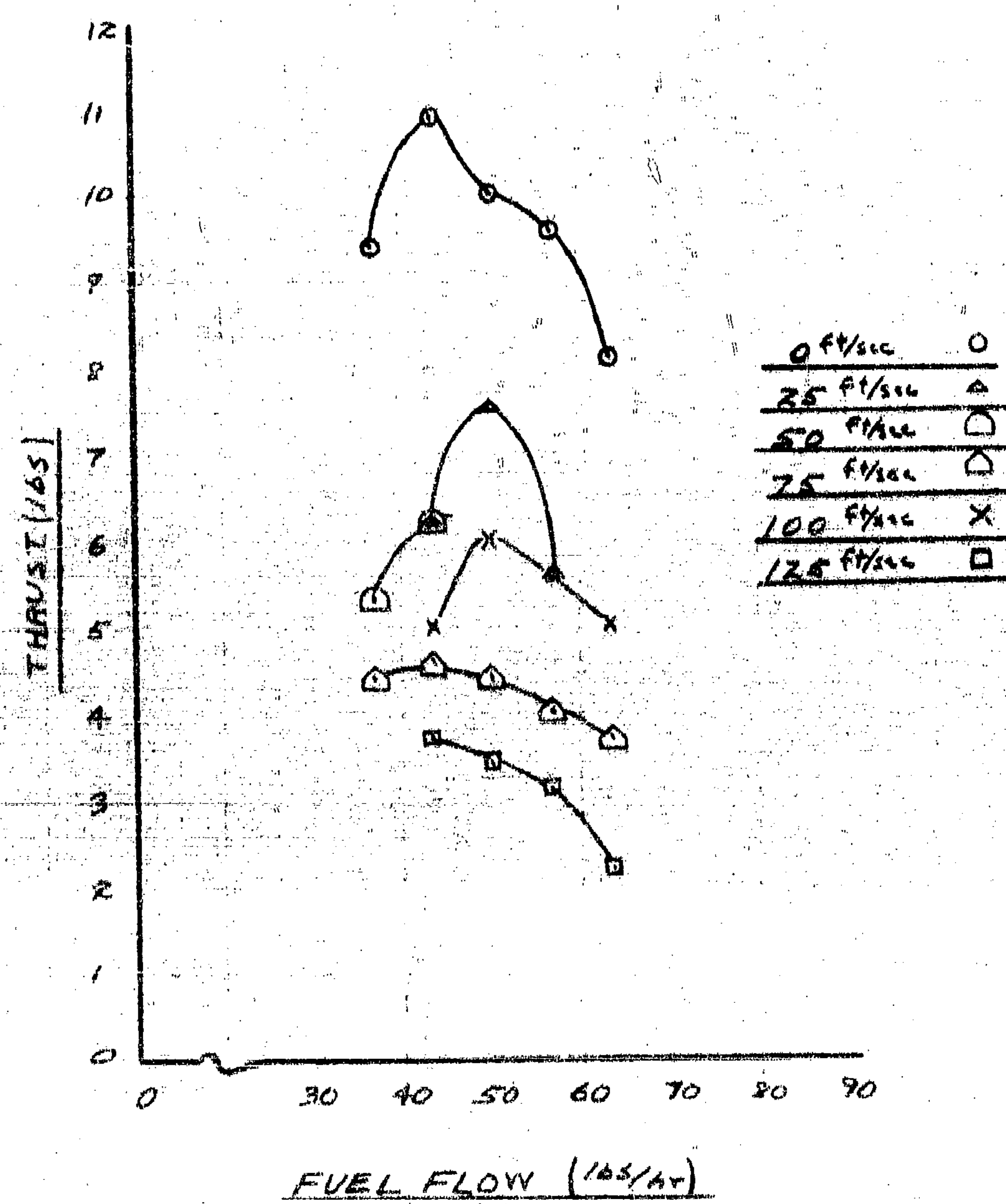
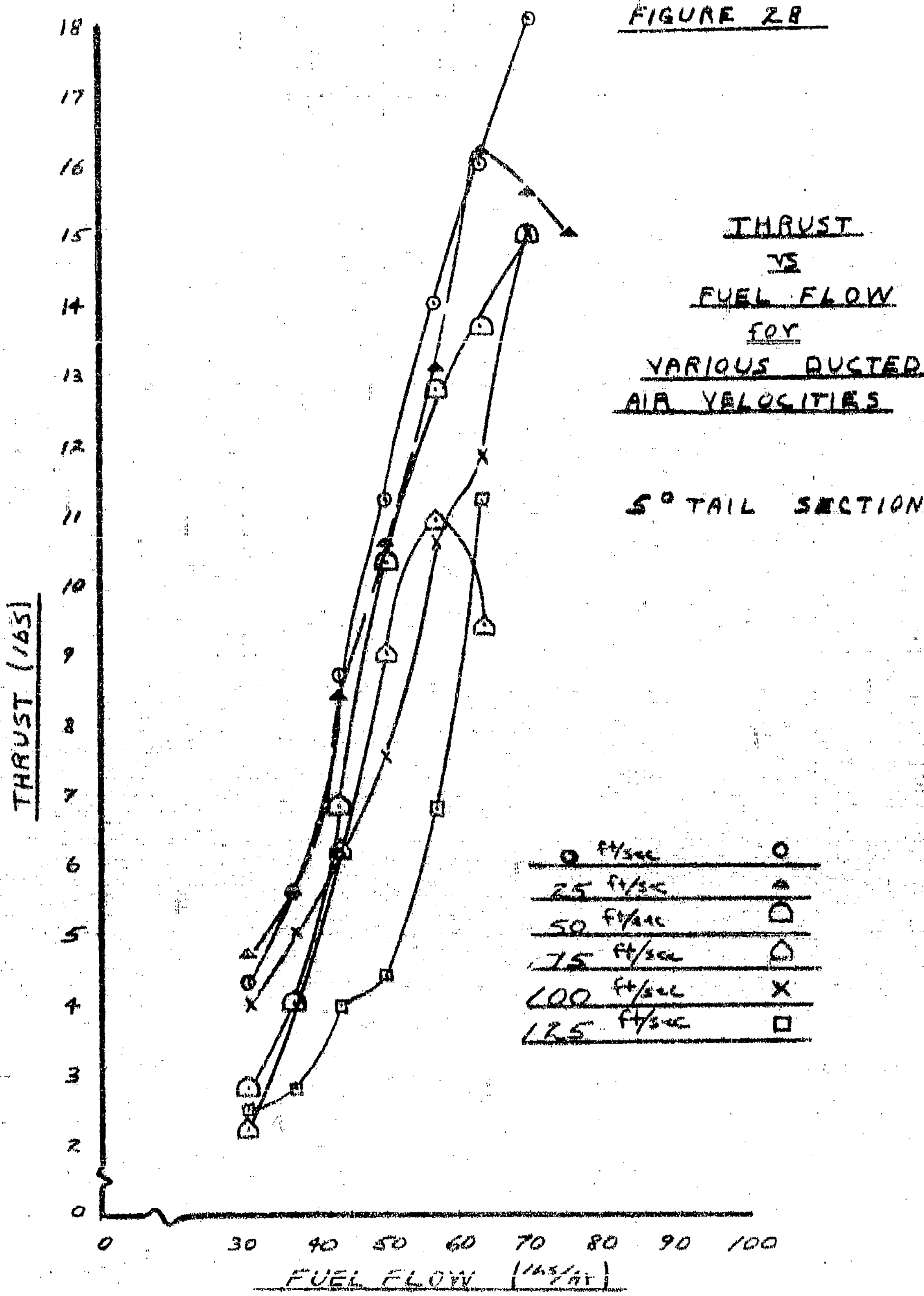


FIGURE 28



THRUST VS FUEL FLOW FOR VARIOUS DUCTED AIR VELOCITIES
5° TAIL SECTION
THRUST (lbs)
FUEL FLOW (lbs/hr)
0 ft/sec
25 ft/sec
50 ft/sec
75 ft/sec
100 ft/sec
125 ft/sec
0
30
40
50
60
70
80
90
100
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

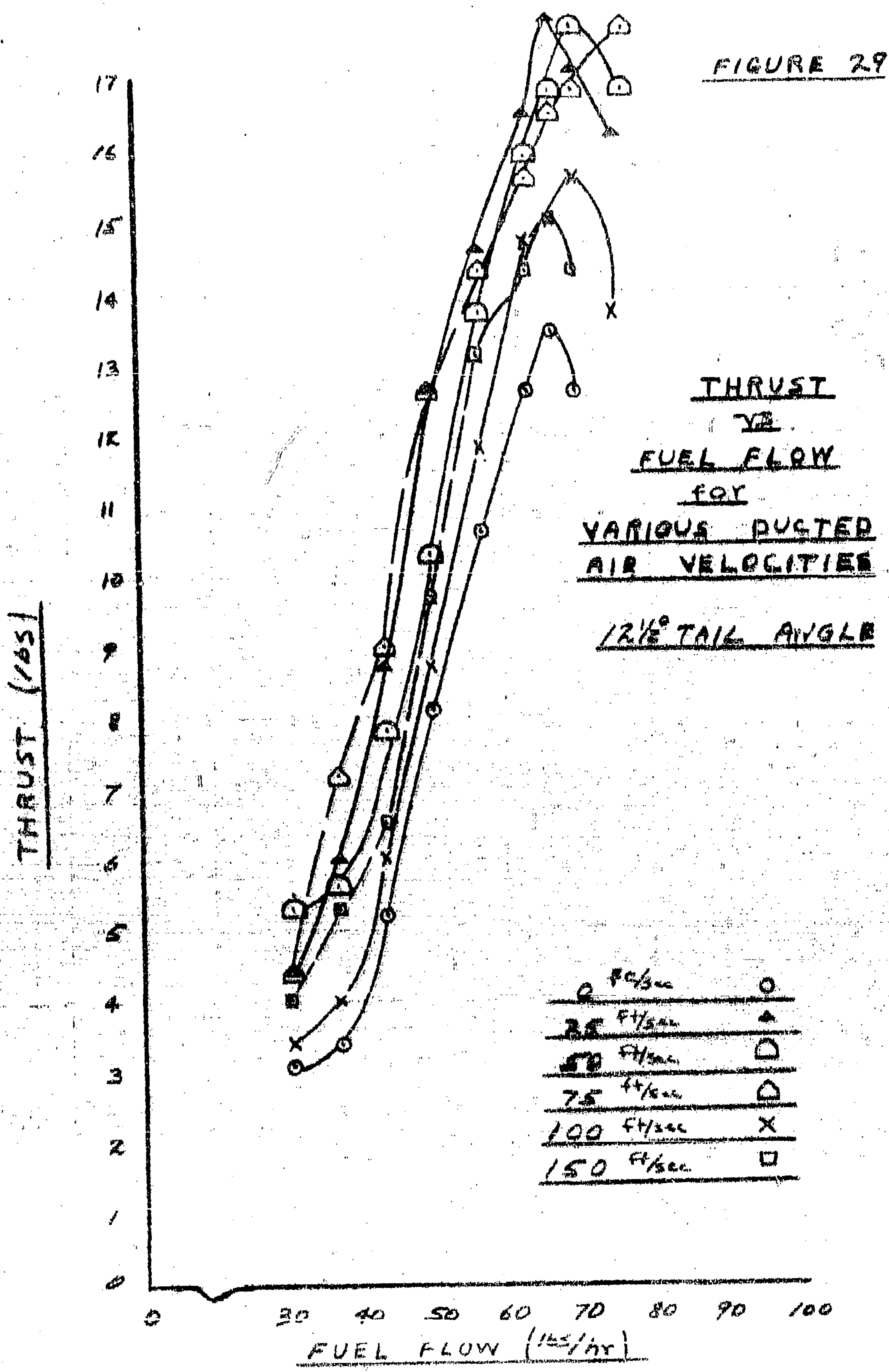


FIGURE 29

THRUST VS FUEL FLOW FOR VARIOUS DUCTED AIR VELOCITIES

12½° TAIL ANGLE

FIGURE 30

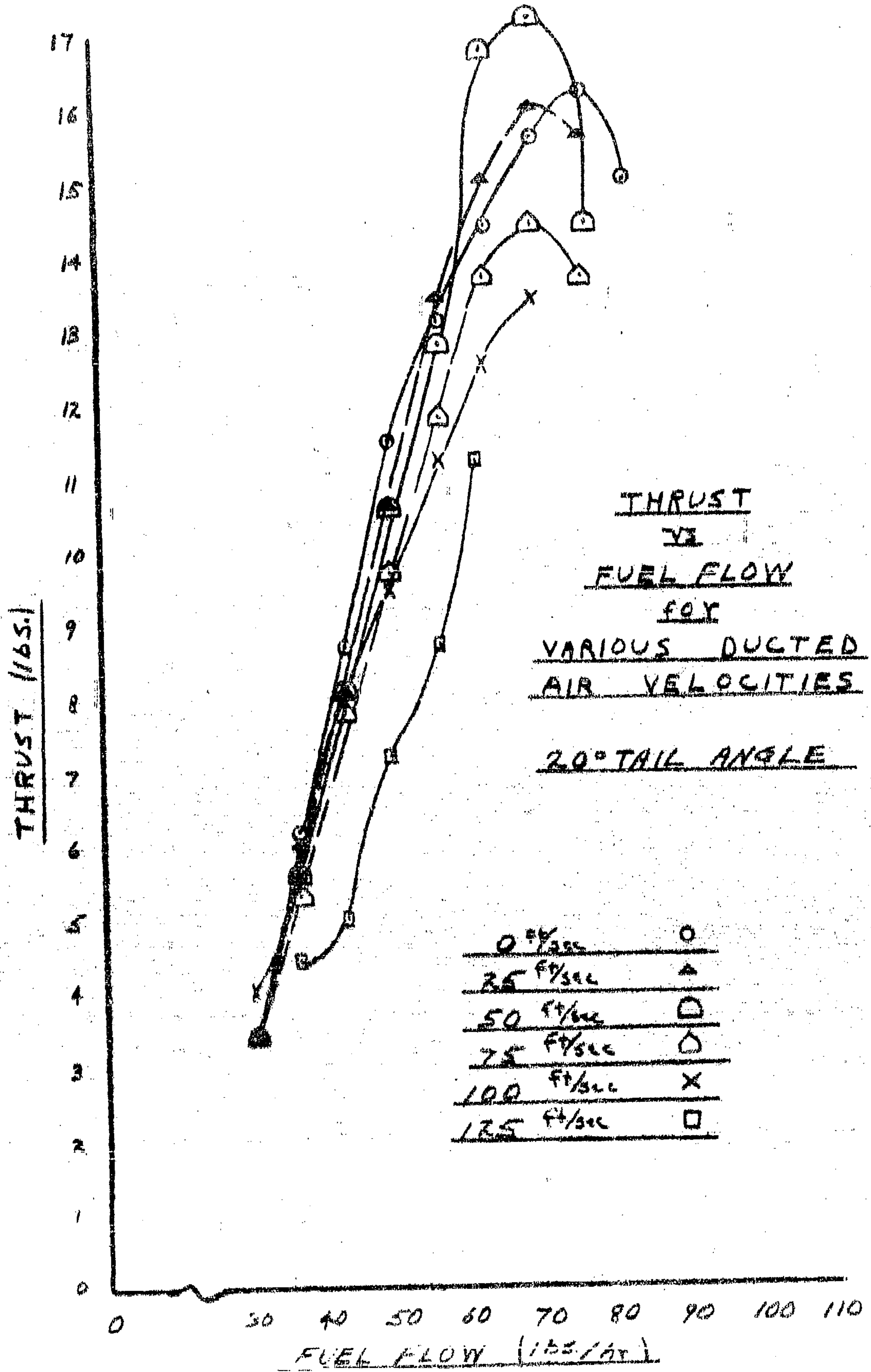

THRUST
VS
FUEL FLOW
FOR
VARIOUS DUCTED
AIR VELOCITIES
20° TAIL ANGLE
0 ft/sec
25 ft/sec
50 ft/sec
75 ft/sec
100 ft/sec
125 ft/sec
THRUST (lbs.)
FUEL FLOW (lbs/hr)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
30
40
50
60
70
80
90
100
110

FIGURE 31

THRUST VS FUEL FLOW
for
VARIOUS DUCTED AIR VELOCITIES

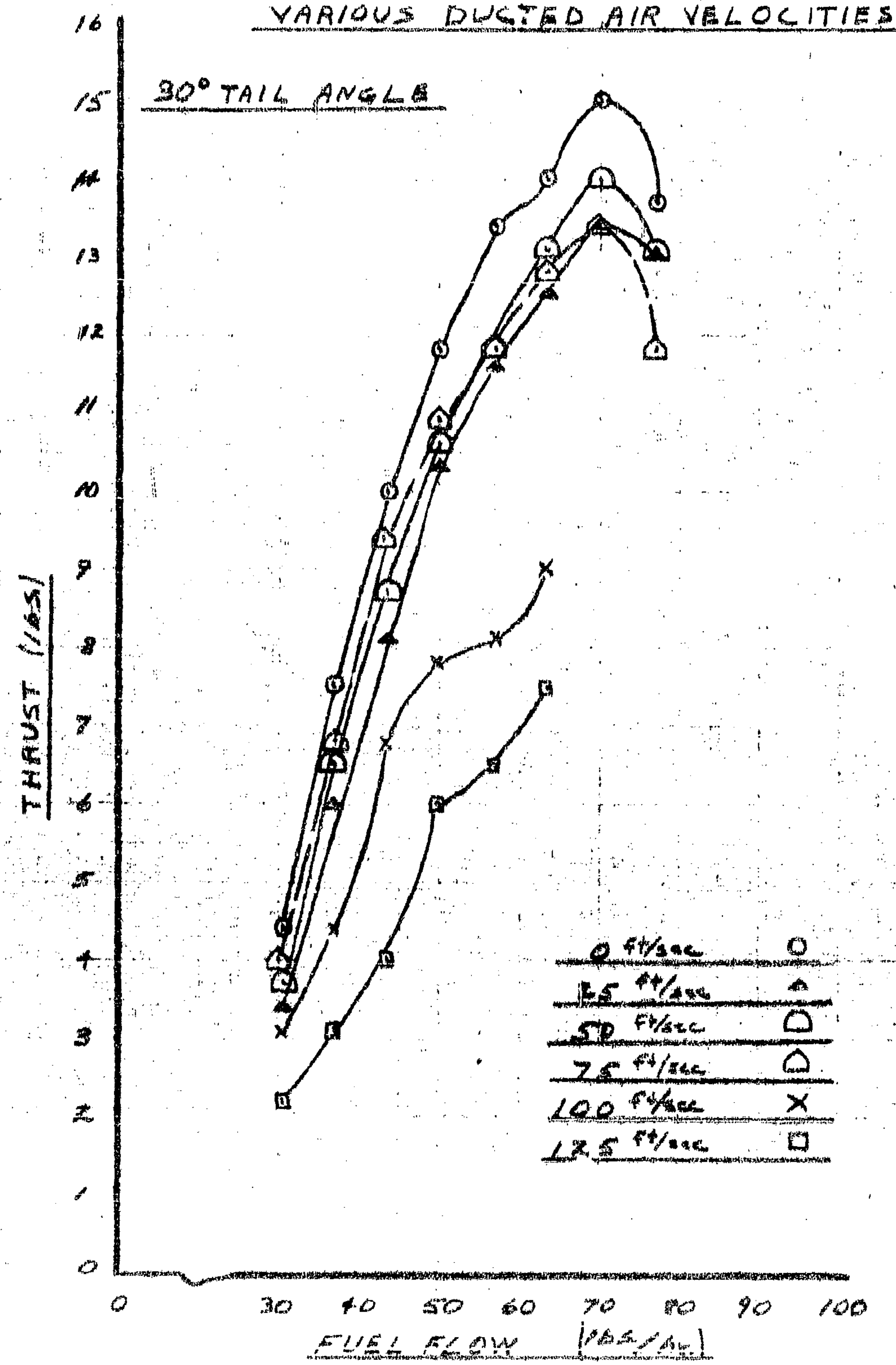


FIGURE 32

COMBUSTION CHAMBER PRESSURE
VS
THRUST
FOR
VARIOUS DUCTED AIR VELOCITIES

0° TAIL SECTION

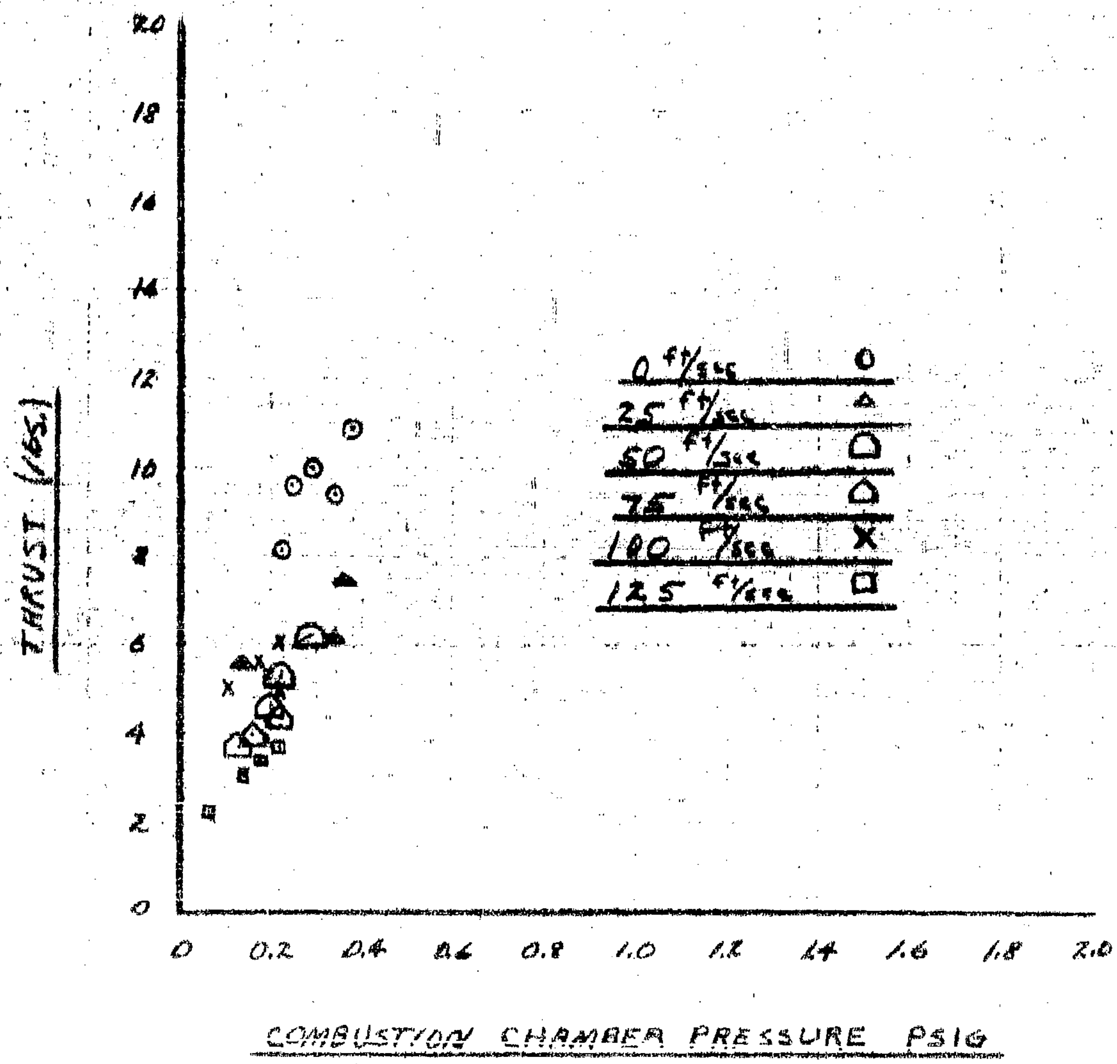


FIGURE 33

COMBUSTION CHAMBER PRESSURE
VS
THRUST
FOR
VARIOUS DUCTED AIR VELOCITIES

5° TAIL SECTION

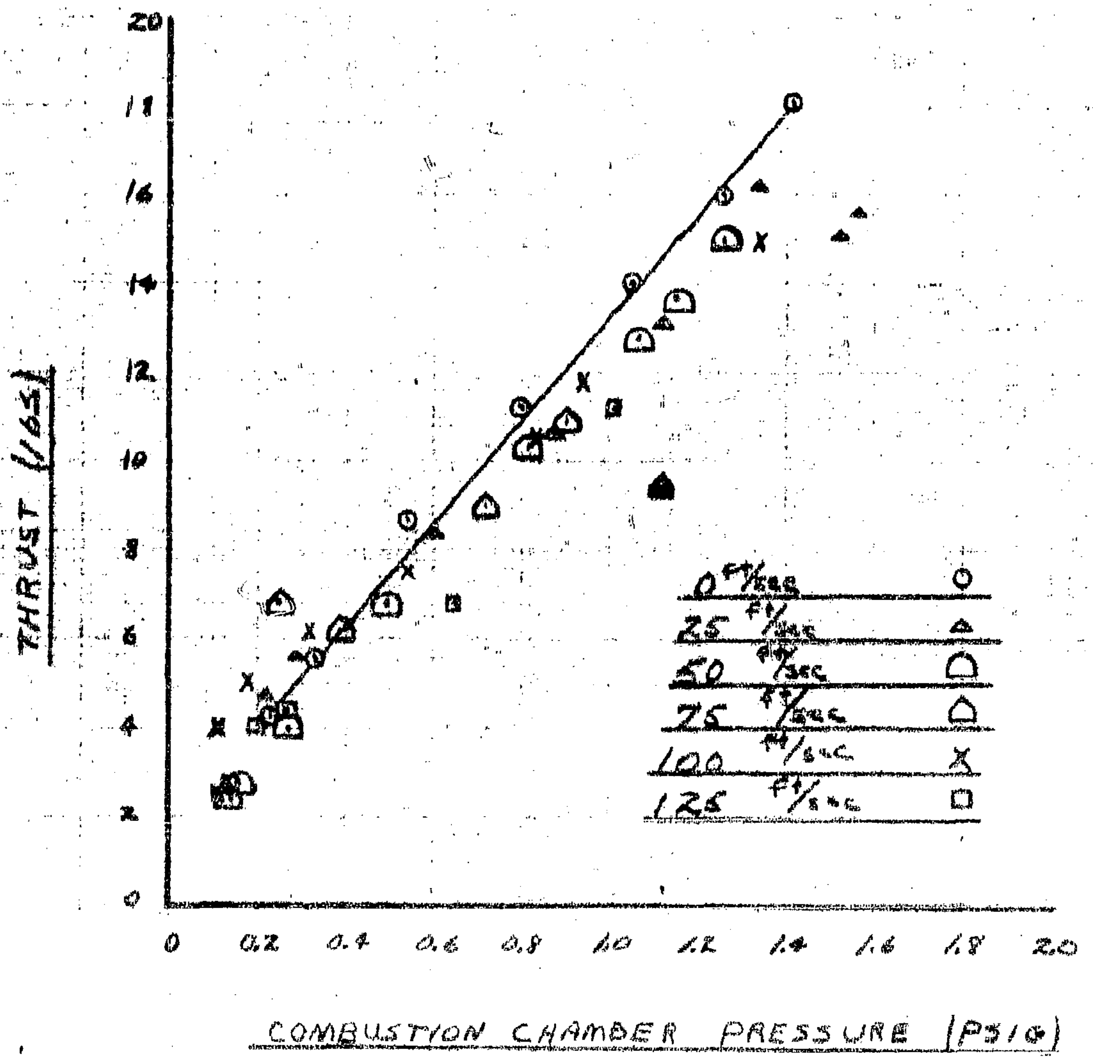


FIGURE 34

COMBUSTION CHAMBER PRESSURE

VS

THRUST

for

VARIOUS DUCTED AIR VELOCITIES

12½° TAIL SECTION

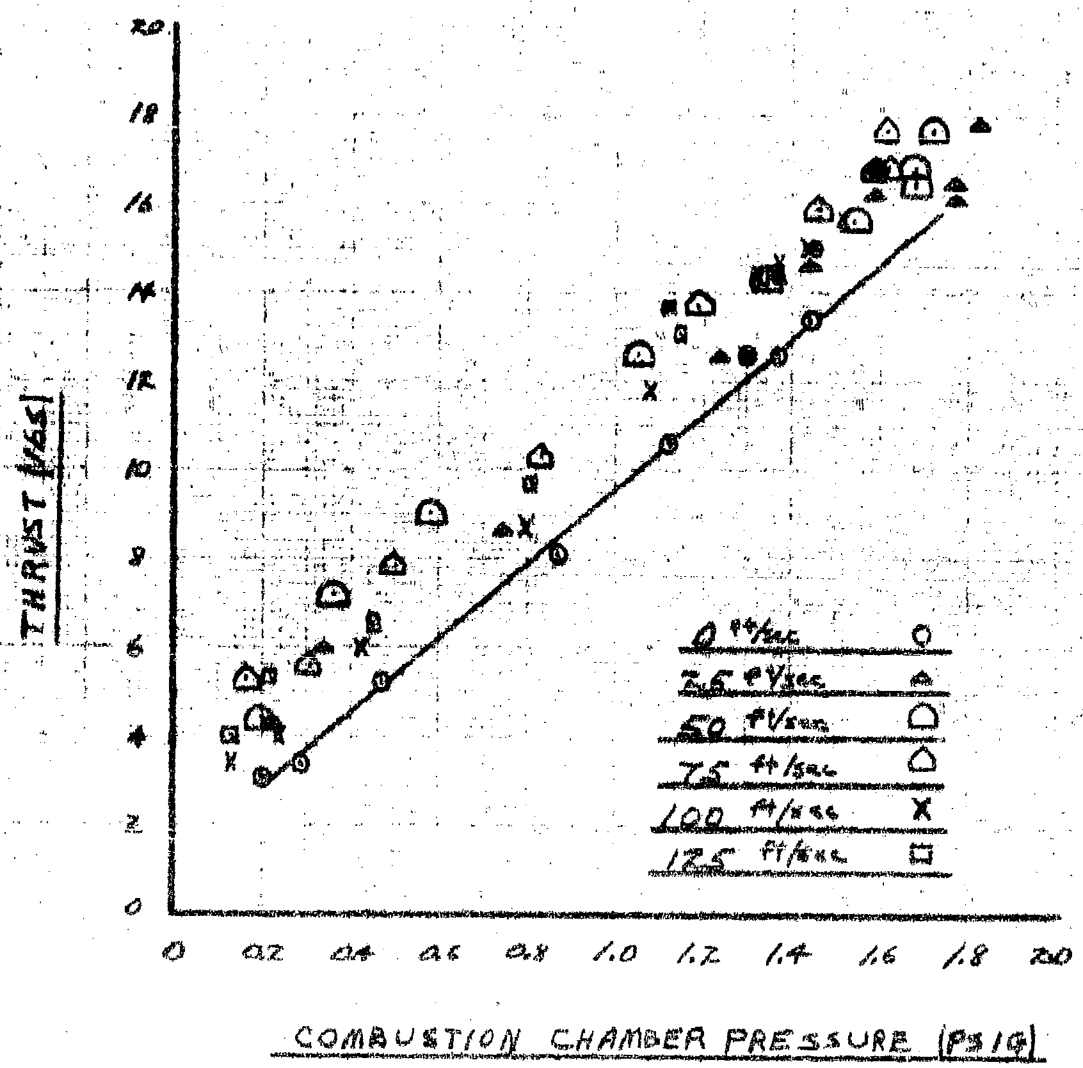


FIGURE 35

COMBUSTION CHAMBER PRESSURE

VS

THRUST

FOR

VARIOUS DUCTED AIR VELOCITIES

20° TAIL SECTION

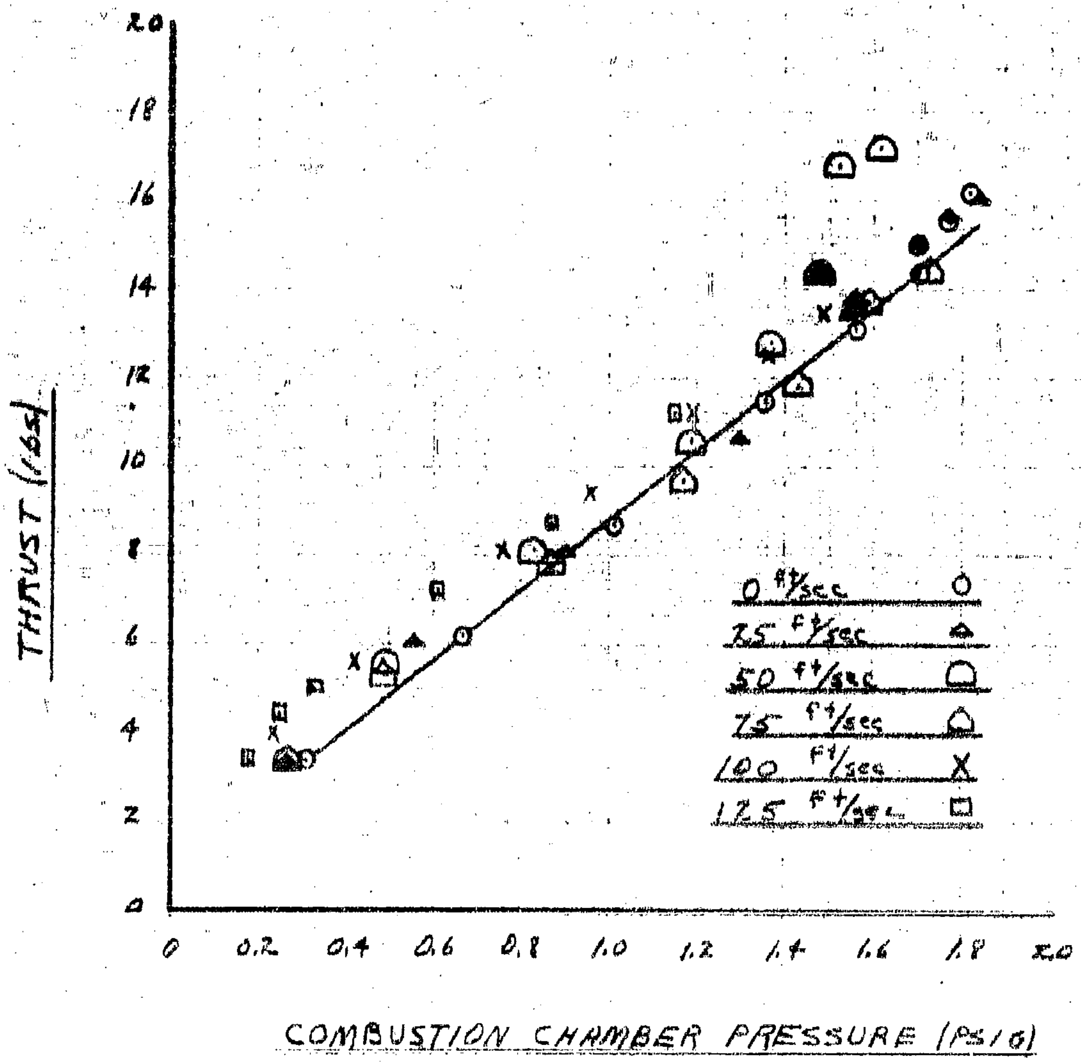


FIGURE 36

COMBUSTION CHAMBER PRESSURE
VS
THRUST
FOR
VARIOUS DUCTED AIR VELOCITIES

30° TAIL SECTION

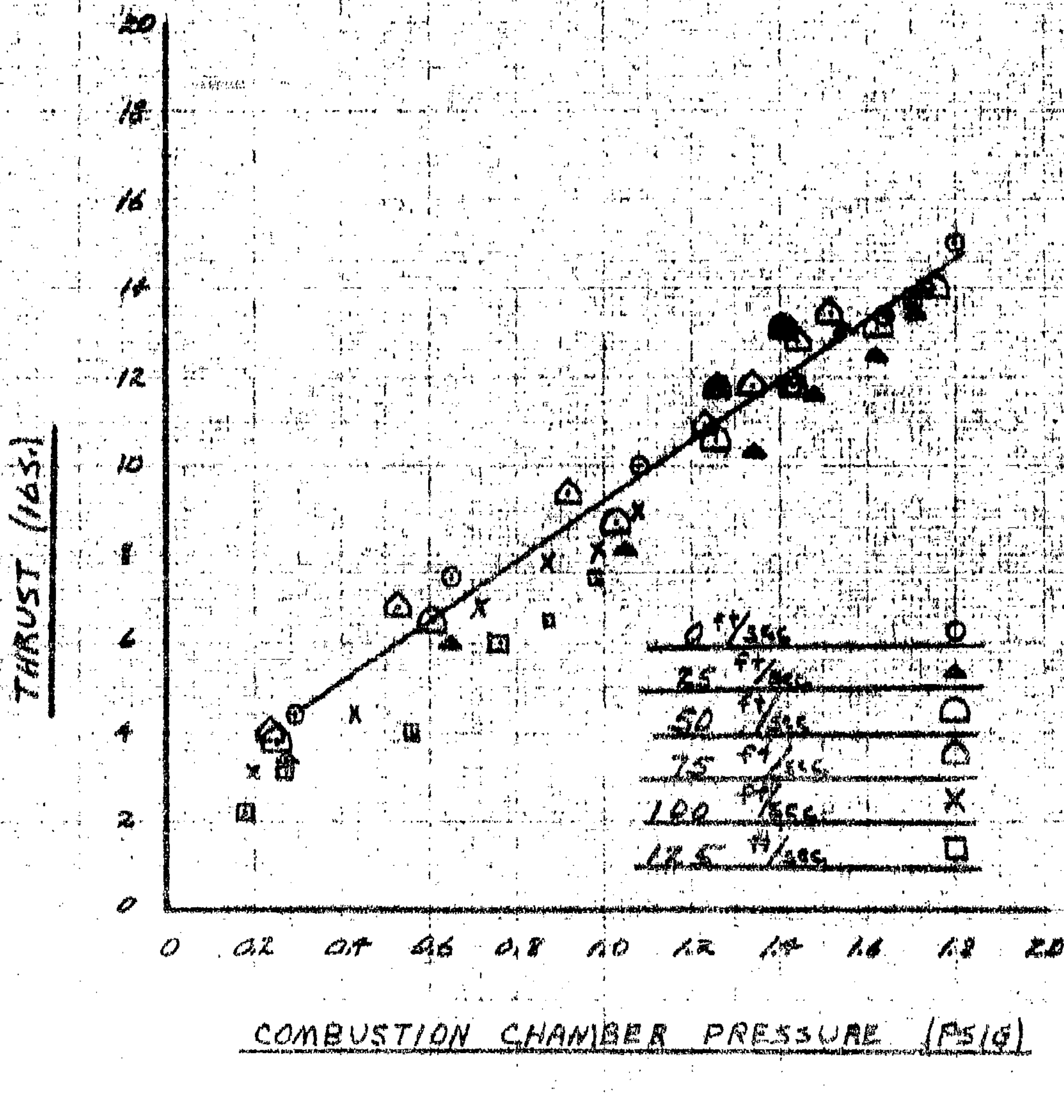


FIGURE 37

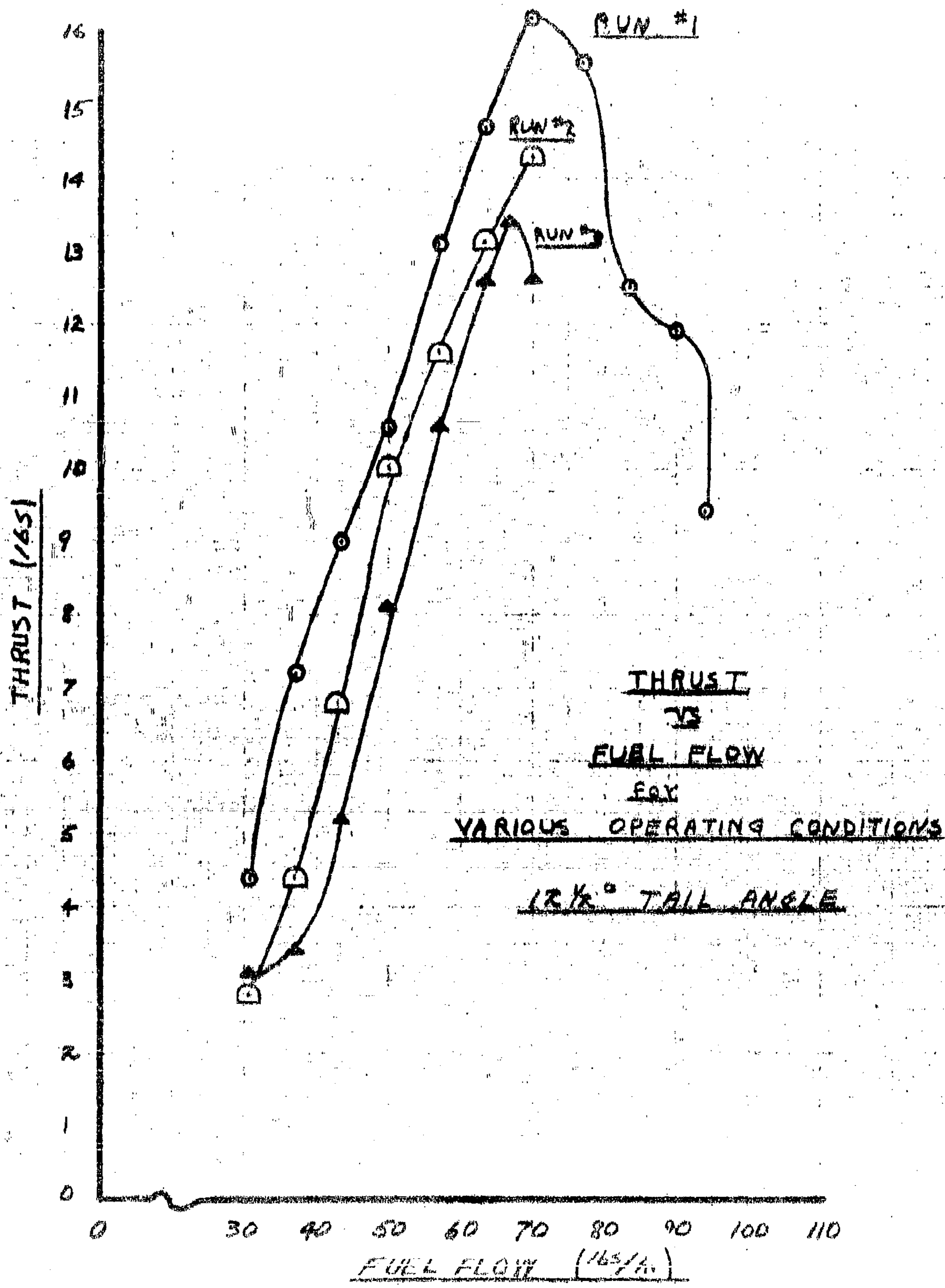

RUN #1
RUN #2
RUN #3
THRUST (lbs)
FUEL FLOW (lbs/hr)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
0
30
40
50
60
70
80
90
100
110
THRUST
VS
FUEL FLOW
FOR
VARIOUS OPERATING CONDITIONS
12½° TAIL ANGLE

FIGURE 38

COMBUSTION CHAMBER PRESSURE
vs
THRUST
for
VARIOUS OPERATING CONDITIONS

12 1/2° TAIL ANGLE

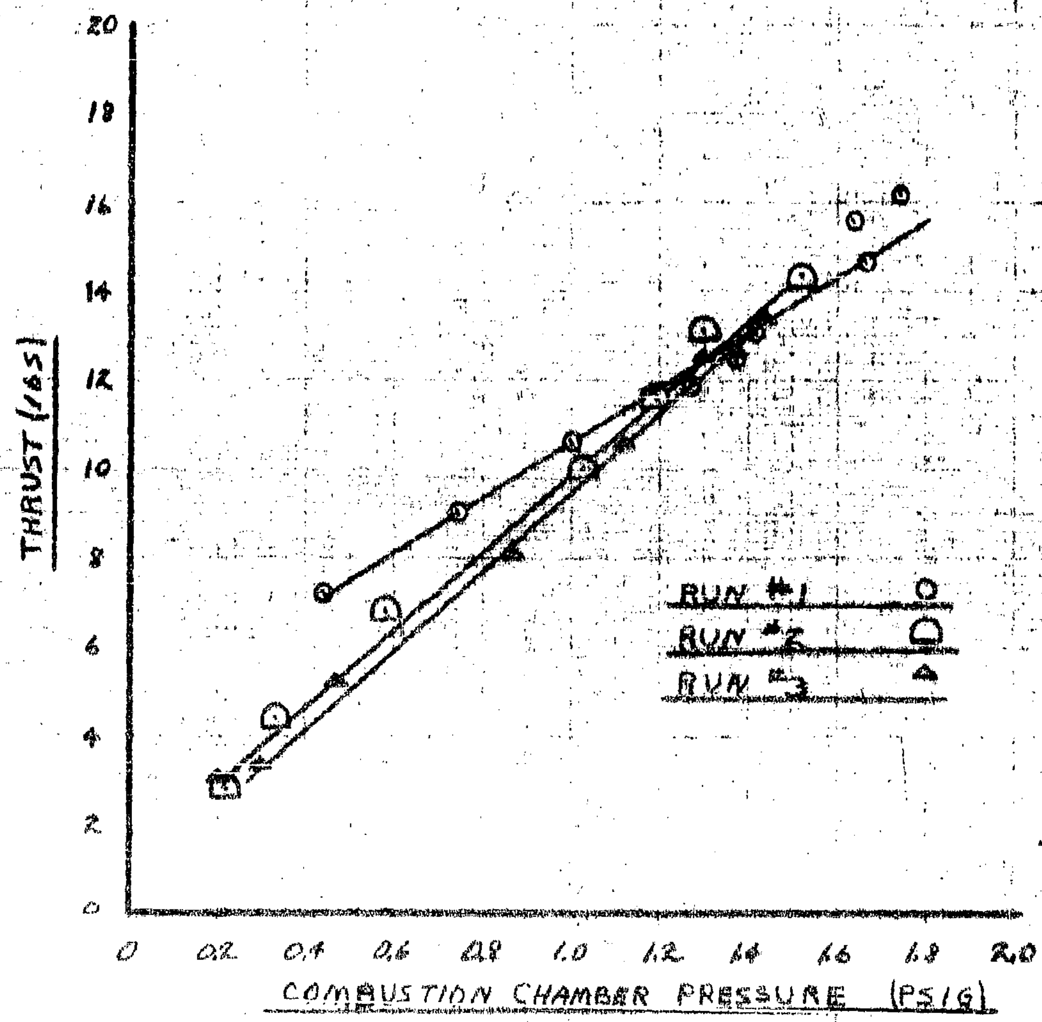


FIGURE 39

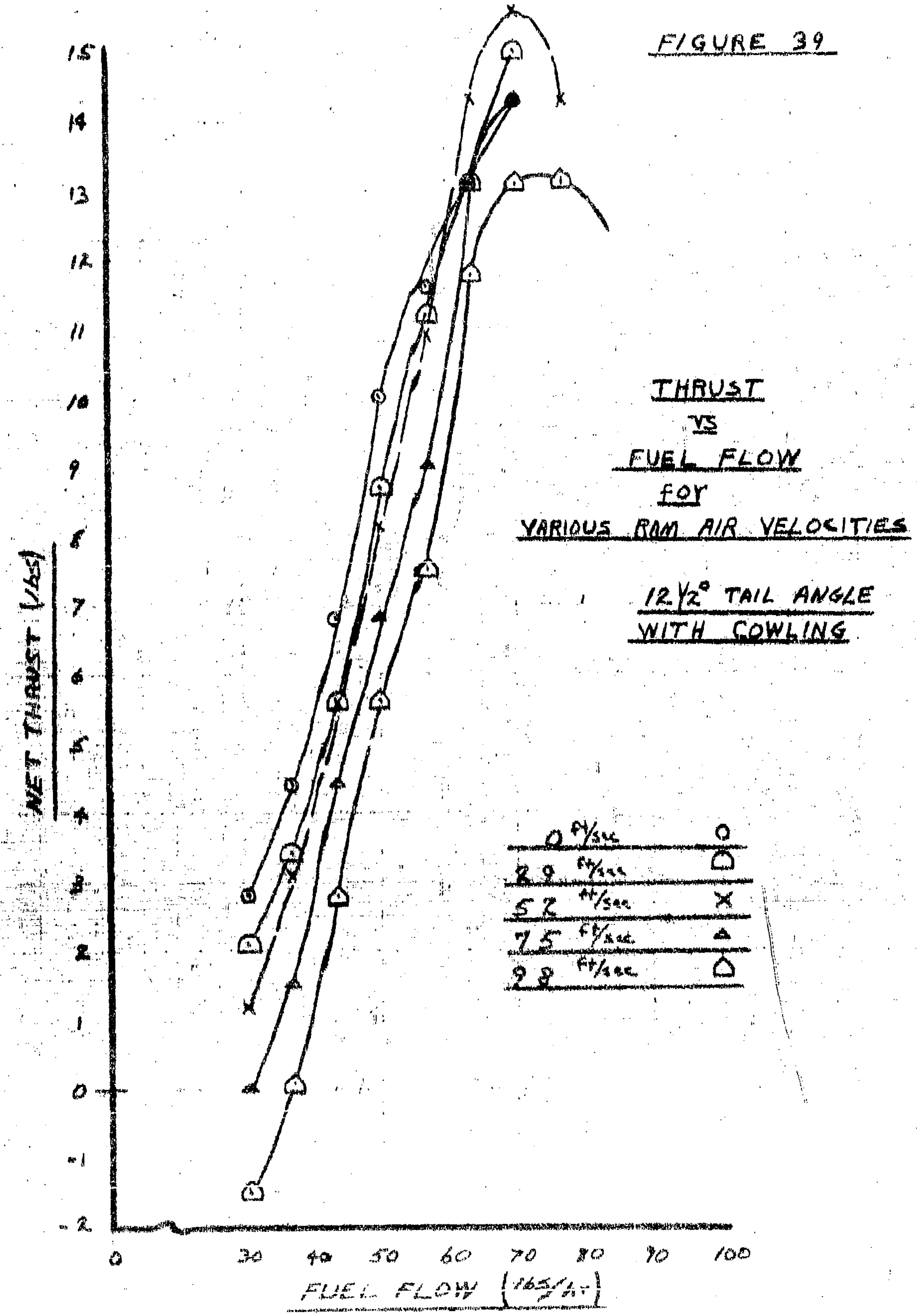

THRUST
VS
FUEL FLOW
FOR
VARIOUS RAM AIR VELOCITIES
12 1/2° TAIL ANGLE
WITH COWLING
0 ft/sec
29 ft/sec
52 ft/sec
75 ft/sec
98 ft/sec
NET THRUST (lbs)
FUEL FLOW (lbs/hr)
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0
30
40
50
60
70
80
90
100

FIGURE 40

FUEL FLOW
VS
THRUST SPECIFIC FUEL CONSUMPTION
FOR
VARIOUS RAM AIR VELOCITIES
WITH COWLING

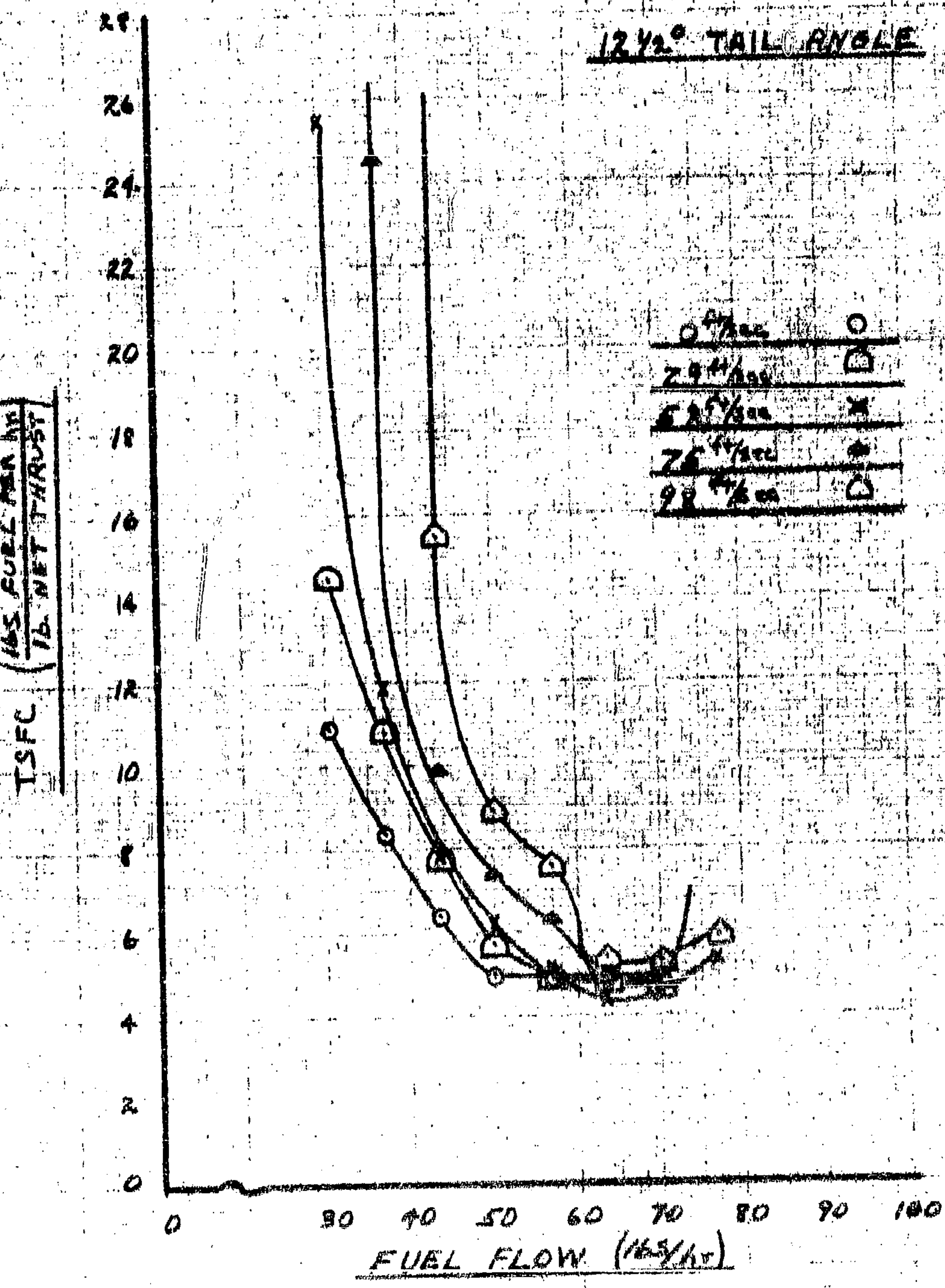
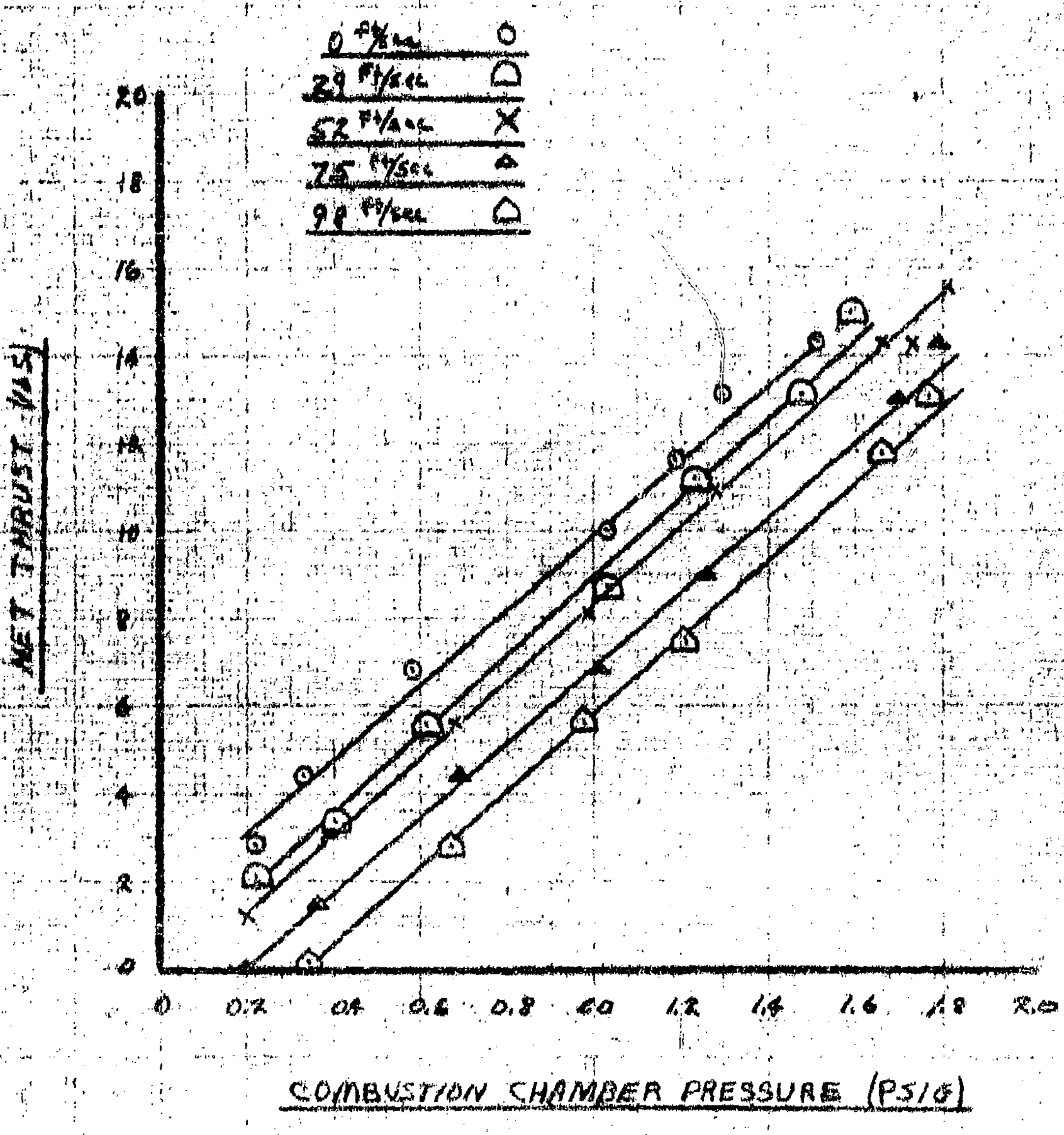


FIGURE 41

COMBUSTION CHAMBER PRESSURE
VS
THRUST
FOR
VARIOUS RAM AIR VELOCITIES

12½° TAIL ANGLE



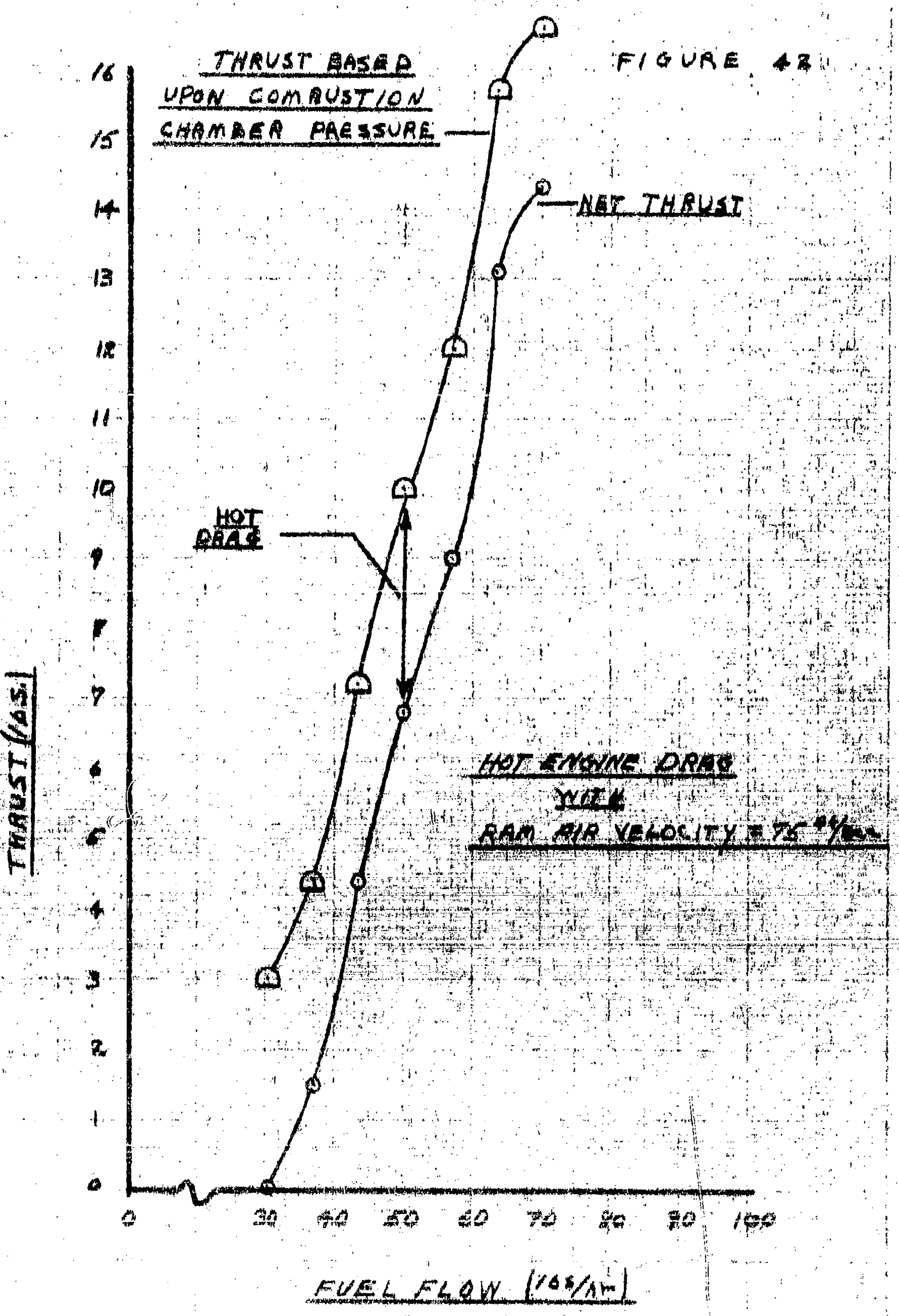

THRUST BASED UPON COMBUSTION CHAMBER PRESSURE
FIGURE 42
NET THRUST
HOT DRAG
HOT ENGINE DRAG WITH RAM AIR VELOCITY = 75
THRUST (LBS)
FUEL FLOW (LBS/HR)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
20
40
50
60
70
80
90
100

FIGURE 43

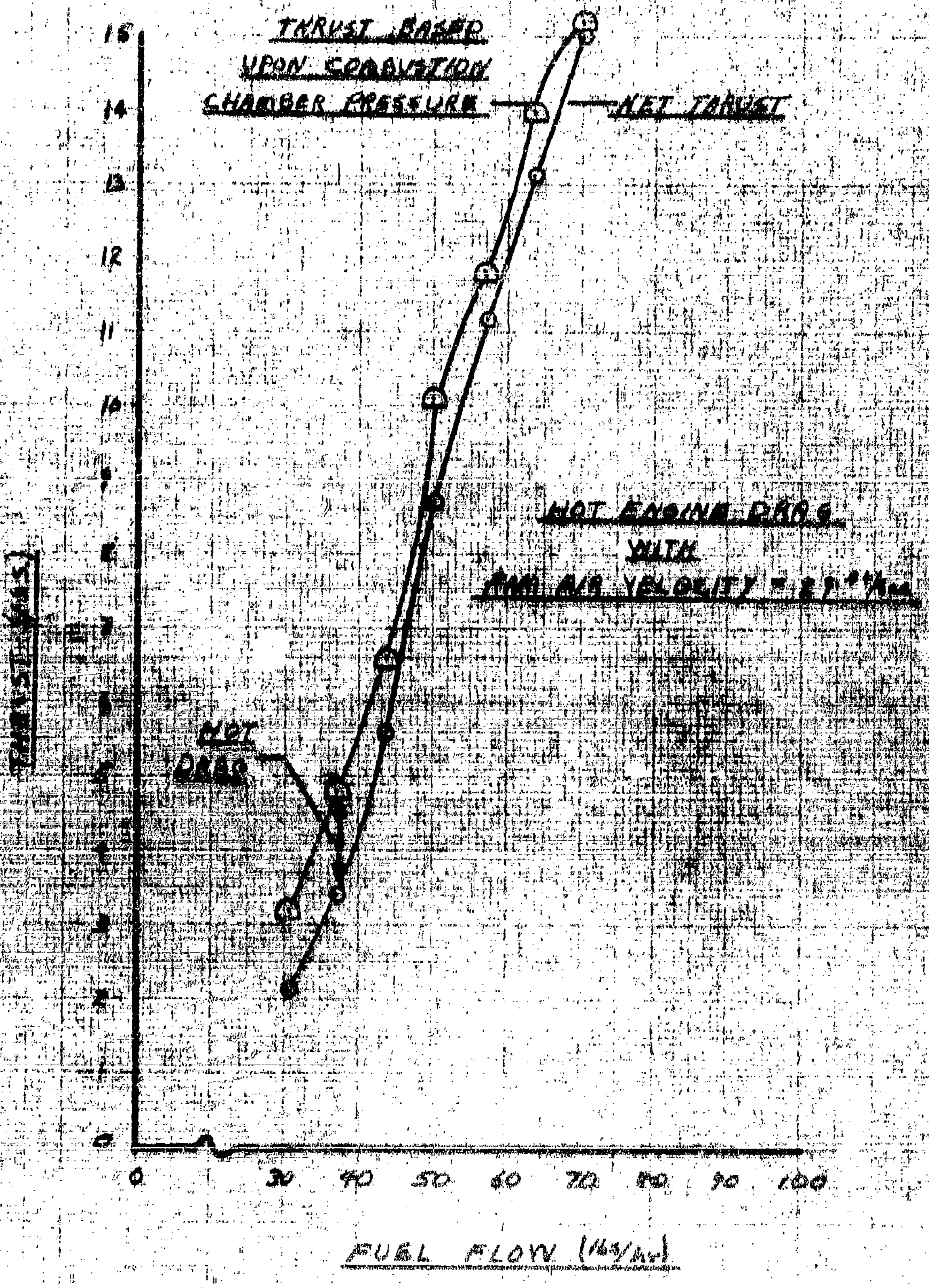
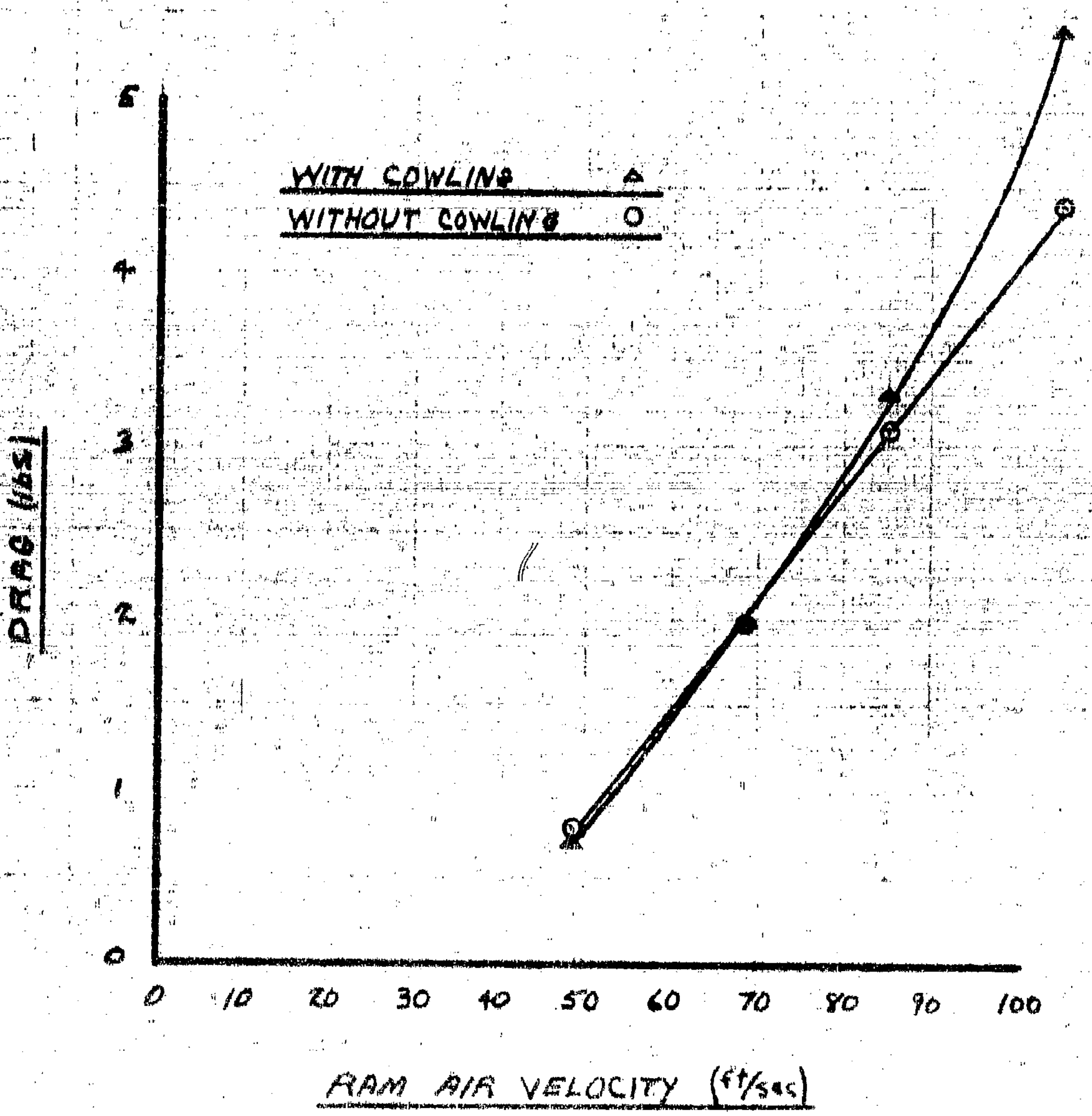

THRUST BASED
UPON COMBUSTION
CHAMBER PRESSURE
NET THRUST
NET DRAG
HOT ENGINE DRAG
WITH
RAM AIR VELOCITY
THRUST (lbs)
0
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0
30
40
50
60
70
80
90
100
FUEL FLOW (lbs/hr)

FIGURE 44

ENGINE DRAG
VS
RAM AIR VELOCITY
for
A COOL ENGINE



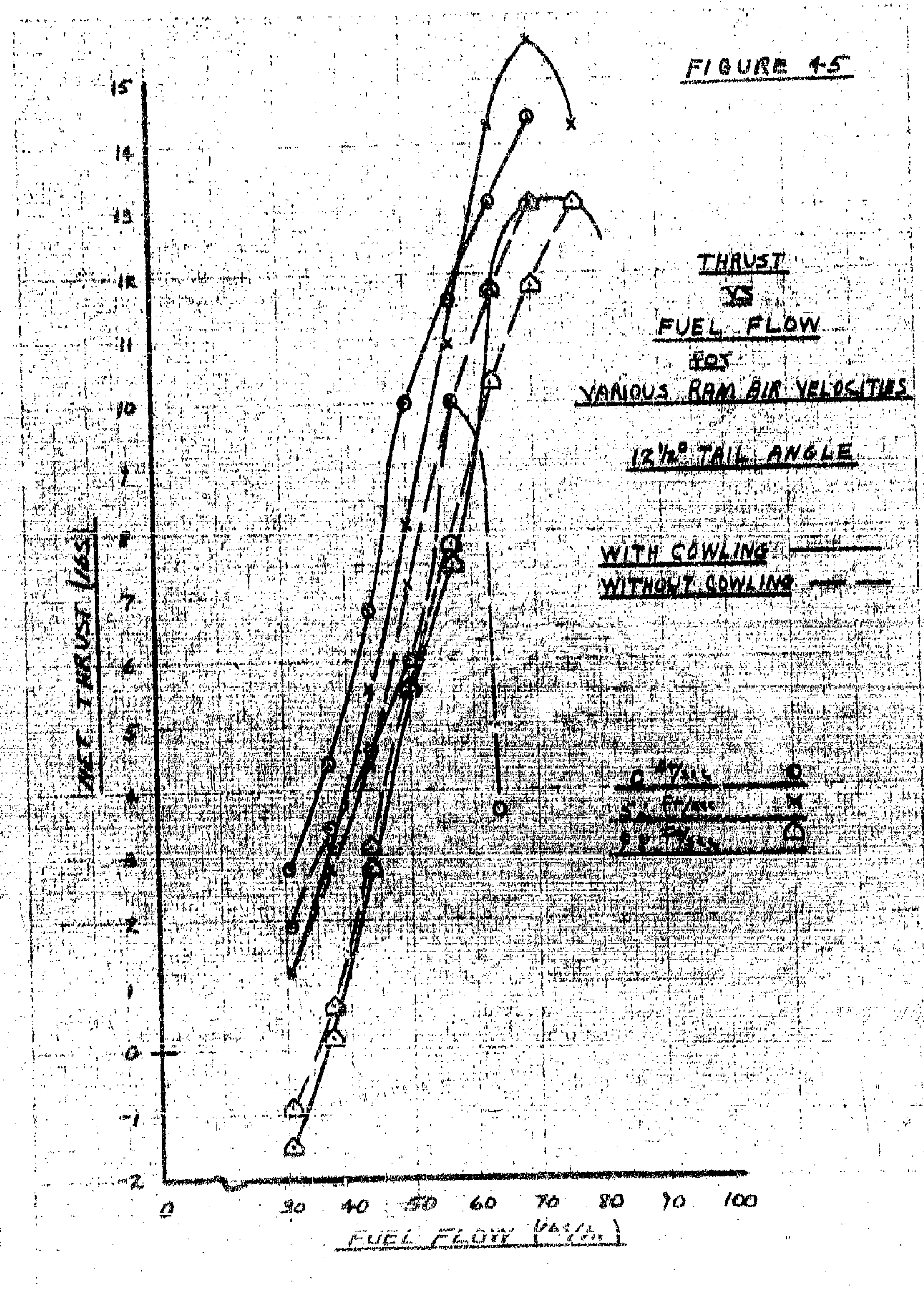
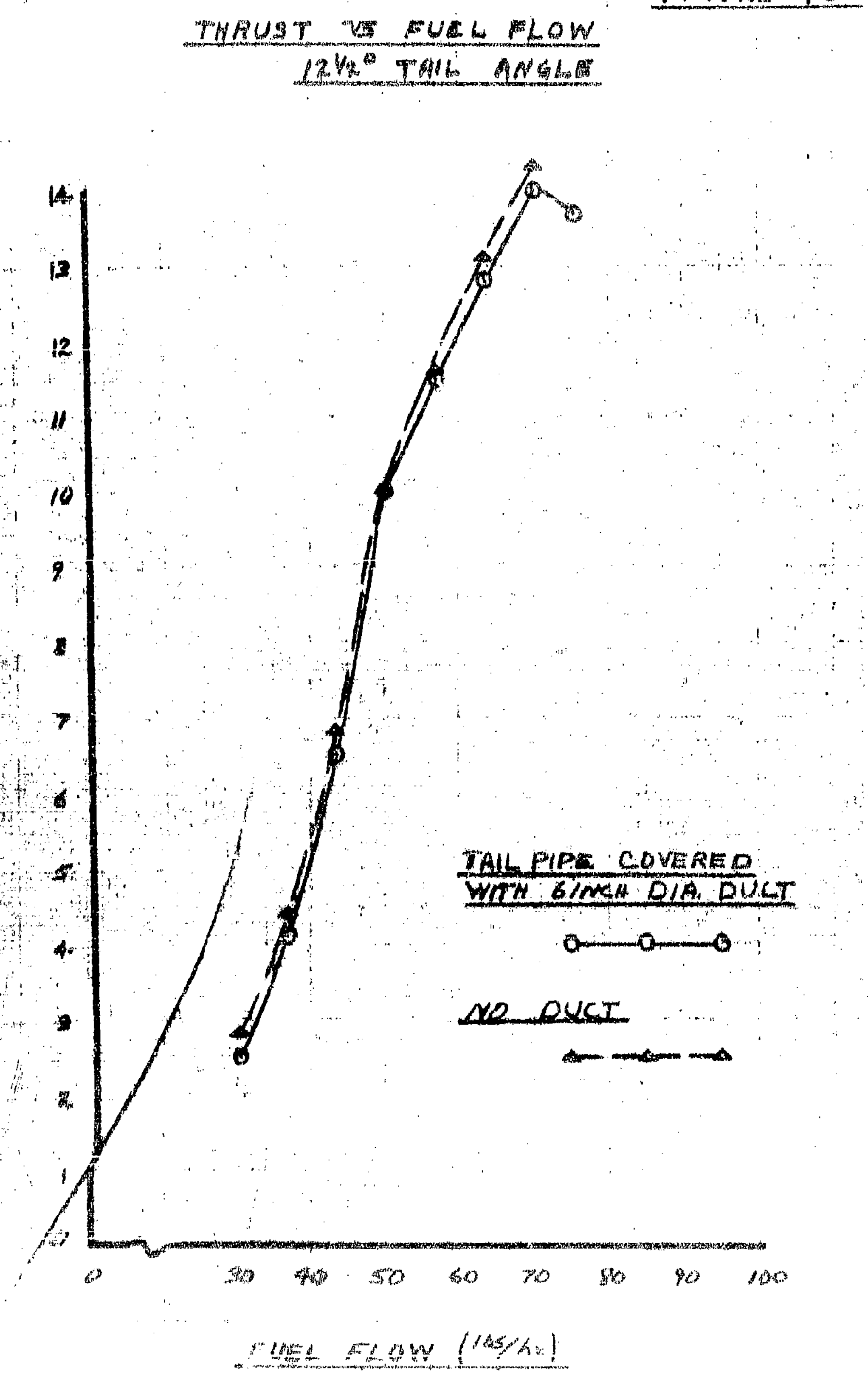


FIGURE 45
THRUST
VS
FUEL FLOW
FOR
VARIOUS RAM AIR VELOCITIES
12½° TAIL ANGLE
WITH COWLING
WITHOUT COWLING
NET THRUST (lbs)
FUEL FLOW
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
0
30
40
50
60
70
80
90
100

FIGURE 46


THRUST VS FUEL FLOW
12½° TAIL ANGLE
THRUST (lbs)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0
30
40
50
60
70
80
90
100
FUEL FLOW (lbs/hr)
TAIL PIPE COVERED WITH 6 INCH DIA. DUCT
NO DUCT

APPENDIX I

DATA for GRAPHS

STATIC CONDITIONS

TAIL ANGLE	FUEL lbs/hr	THRUST lbs	COMB. Ch. PRESS. P.S.I.G.	EXHAUST TEMP °F	TAIL ANGLE	FUEL lbs/hr	THRUST lbs	COMB. CH. PRESS. P.S.I.G.	EXHAUST TEMP °F
0°	30.5	2.45	0.706	1600	30°	36.8	3.1	0.453	—
	36.8	5.20	0.424	1540		43.5	5.0	0.706	1460
	43.5	6.50	0.561	1740		50.0	6.5	0.905	1460
	50.0	7.50	0.670	1790		56.8	8.1	1.120	1420
	56.8	8.40	0.742	1790		63.5	9.7	1.410	1460
	63.5	7.50	0.651	1780		70.0	11.2	1.520	1500
	70.0	5.00	0.453	—		76.8	10.3	1.374	1560
						83.5	6.8	0.796	1680
5°	30.5	2.8	—	-		90.0	5.0	0.580	—
	36.8	5.2	0.420	-					
	43.5	7.0	0.597	-	45°	36.8	2.8	0.507	1480
	50.0	8.1	0.760	-		43.5	4.3	0.742	1560
	56.8	11.2	1.012	-		50.0	5.6	0.940	1600
	63.5	13.1	1.250	-		56.8	7.5	1.210	1620
	70.0	14.4	1.374	-		63.5	8.8	1.393	1620
	76.8	13.1	1.192	-		70.0	9.0	1.410	—
	82.0	7.5	0.724	-		76.8	8.8	1.340	—
						83.5	6.8	0.778	—
12½°	30.5	4.4	—	—		90.0	3.7	0.326	—
	36.8	7.2	0.435	—		97.0	3.7	0.290	—
	43.5	9.0	0.742	—		103.0	3.1	0.109	—
	50.0	10.6	0.996	—					
	56.8	13.1	1.410	—	-10°	43.5	2.4	0.163	OVER 2000°F
	63.5	14.7	1.662	—		50.0	3.4	0.199	
	70.0	16.2	1.736	—		56.8	3.4	0.199	
	76.8	15.6	1.630	—		63.5	3.1	0.181	
	83.5	12.5	1.374	—		70.0	3.1	0.183	
	90.0	11.9	1.267	—		76.8	3.0	0.163	
	93.8	9.4	1.025	—		83.5	2.4	0.123	
20°	31.0	4.4	0.344	—					
	36.8	6.0	0.507	1460					
	43.5	8.2	0.742	1480					
	50.0	9.7	1.013	—					
	56.8	11.2	1.274	1600					
	63.5	13.7	1.590	—					
	70.0	15.6	1.920	—					
	76.8	15.0	1.770	1630					
	83.5	13.1	1.300	—					
	90.0	11.7	1.160	—					
	97.0	9.4	0.977	—					

DUCTED AIR TESTS

30°

AIR VELOCITY ft/sec	FUEL lbs/hr	THRUST lbs.	COMB. CH. PRESS. P.S.I.G.
0	30.5	4.4	0.289
	36.8	7.5	0.650
	43.5	10.0	1.083
	50.0	11.8	1.427
	56.8	13.4	1.640
	63.5	14.0	1.730
	70.0	15.0	1.805
	76.8	13.7	1.700
26	30.5	3.4	0.271
	36.8	6.0	0.650
	43.5	8.1	1.050
	50.0	10.3	1.337
	56.8	11.6	1.480
	63.5	12.5	1.625
	70.0	13.4	1.715
	76.8	13.1	1.555
50	30.5	2.7	0.253
	36.8	6.5	0.615
	43.5	8.7	1.030
	50.0	10.6	1.265
	56.8	11.8	1.427
	63.5	13.1	1.625
	70.0	14.0	1.750
	76.8	13.1	1.410
75	30.5	4.0	0.235
	36.8	6.8	0.525
	43.5	9.4	0.925
	50.0	10.9	1.230
	56.8	11.8	1.337
	63.5	12.8	1.445
	70.0	13.4	1.520
	76.0	11.8	1.265
100	30.5	3.1	0.199
	36.8	4.4	0.434
	43.5	5.8	0.724
	50.0	7.8	0.868
	56.8	8.1	0.976
	63.5	9.0	1.083
125	30.5	2.2	0.108
	36.8	3.1	0.271
	43.5	4.0	0.560
	50.0	6.0	0.760
	56.8	6.5	0.868
	63.5	7.5	0.976

20°

AIR VELOCITY ft/sec	FUEL lbs/hr	THRUST lbs.	COMB. CH. PRESS. P.S.I.G.
0	30.5	3.4	0.307
	36.8	6.2	0.667
	43.5	8.7	1.010
	50.0	11.5	1.355
	56.8	13.1	1.555
	63.5	14.4	1.700
	70.0	15.6	1.770
	76.8	16.2	1.824
	82.5	15.0	1.700
25	30.5	3.4	0.271
	36.8	6.0	0.560
	43.5	8.1	0.905
	50.0	10.6	1.300
	56.8	13.4	1.535
	63.5	15.0	1.700
	70.0	16.0	1.841
	76.8	15.6	1.770
50	30.5	3.4	0.271
	36.8	5.6	0.488
	43.5	8.1	0.810
	50.0	10.6	1.190
	56.8	12.8	1.370
	63.5	16.8	1.520
	70.0	17.2	1.625
	77.5	14.4	1.480
75	30.5	3.4	0.271
	36.8	6.3	0.488
	43.5	7.8	0.868
	50.0	9.7	1.173
	56.8	11.8	1.430
	63.5	13.7	1.590
	70.0	14.4	1.716
	76.8	13.7	1.555
100	30.5	4.0	0.235
	36.8	5.6	0.416
	43.5	8.1	0.760
	50.0	9.4	0.960
	56.8	11.2	1.190
	63.5	12.5	1.355
	70.0	13.4	1.480
125	30.5	3.4	0.182
	36.8	4.4	0.253
	43.5	5.0	0.325
	50.0	7.2	0.614
	56.8	8.7	0.868
	63.0	11.2	1.035

DUCTED AIR FLOW CONT.

12½°

AIR VEL. ft/sec	FUEL lbs/hr	THRUST lbs	COMB. CH. PRESS. PSIG.	EXHAUST TEMP °F
0	30.5	3.1	0.199	1900
	36.8	3.4	0.289	1900
	43.5	5.2	0.470	1760
	50.0	8.1	0.866	1640
	56.8	10.6	1.120	1600
	63.5	12.6	1.373	1580
	67.0	13.4	1.445	—
	70.0	12.6	1.300	—
25	30.5	4.4	0.217	2000
	36.8	6.0	0.343	2000
	43.5	8.7	0.721	1900
	50.0	12.6	1.227	1560
	56.8	14.6	1.445	1450
	63.5	16.5	1.770	1460
	67.0	17.8	1.820	—
	70.0	17.1	1.770	—
	75.5	16.2	1.590	—
50	30.5	4.4	0.199	1800
	36.8	7.2	0.361	1880
	43.5	9.0	0.578	1750
	50.0	12.6	1.097	1600
	56.8	14.3	1.337	1610
	63.5	15.6	1.535	1560
	67.0	16.5	1.680	1540
	70.0	16.8	1.680	1560
	76.8	17.7	1.715	—
75	30.5	5.3	0.162	1800
	36.8	5.6	0.307	1760
	43.5	7.8	0.505	1780
	50.0	10.3	0.830	1680
	56.8	13.7	1.190	1630
	63.5	15.9	1.461	1600
	67.0	16.8	1.625	1590
	70.0	17.7	1.625	1600
	76.8	16.8	1.590	—
100	30.5	3.4	0.126	1880
	36.8	4.0	0.235	1870
	43.5	6.0	0.415	1780
	50.0	8.7	0.795	1670
	56.8	11.8	1.082	1660
	63.5	14.7	1.370	1630
	67.0	15.0	1.444	1600
	70.0	15.6	1.520	1610
	75.5	13.7	1.120	—
125	30.5	4.0	0.126	1850
	36.8	5.2	0.217	1830
	43.5	6.5	0.451	1750
	50.0	9.7	0.811	1520
	56.8	13.1	1.155	1620
	63.5	14.3	1.335	1590
	67.0	15.0	1.445	1580
	70.0	14.3	1.370	1600

5°

AIR VEL. ft/sec	FUEL lbs/hr	THRUST lbs	COMB. CH. PRESS. PSIG.	EXHAUST TEMP °F
0	30.5	4.3	0.234	1840
	36.8	5.6	0.325	1880
	43.5	8.7	0.541	1780
	50.0	11.2	0.795	1720
	56.8	14.0	1.047	1600
	63.5	16.0	1.263	1500
	70.0	18.1	1.410	1460
25	30.5	4.7	0.216	1900
	36.8	5.6	0.288	1980
	43.5	8.4	0.596	1800
	50.0	10.6	0.866	1730
	56.8	13.1	1.120	1700
	63.5	16.2	1.337	1640
	70.0	15.6	1.555	1580
	76.0	15.0	1.518	—
50	30.5	2.8	0.163	1900
	36.8	4.0	0.271	1950
	43.5	6.8	0.487	1840
	50.0	10.3	0.814	1630
	56.8	12.8	1.065	1560
	63.5	13.7	1.156	1550
	70.0	15.0	1.263	—
75	30.5	2.2	0.144	1800
	36.8	—	—	—
	43.5	6.2	0.396	—
	50.0	7.0	0.722	—
	56.8	10.7	0.902	—
	63.5	9.4	1.120	—
100	30.5	4.0	0.109	2000
	36.8	5.0	0.180	1860
	43.5	6.2	0.325	1800
	50.0	7.5	0.541	1820
	56.8	10.6	0.830	1650
	63.5	11.8	0.940	—
	70.0	15.0	1.337	—
125	30.5	2.5	0.109	2050
	36.8	2.8	0.144	1970
	43.5	4.0	0.199	1880
	50.0	4.4	0.271	1900
	56.8	6.8	0.550	—
	63.5	11.2	0.810	—

DUCTED AIR FLOW CONT.

0°

AIR VELOCITY ft/sec	FUEL lbs/hr	COMB. CH. PRESS. PSIG.	THRUST lbs	EXHAUST TEMP. °F
0	36.8	0.343	9.4	1750
	43.5	0.380	10.9	2000
	50.0	0.289	10.0	2000
	56.8	0.253	9.6	2000
	63.5	0.217	8.4	2000
25	43.5	0.343	6.2	2000
	50.0	0.361	7.5	2000
	56.8	0.144	5.6	2000
50	36.8	0.217	5.3	1600
	43.5	0.289	6.2	—
75	36.8	0.217	4.4	1660
	43.5	0.198	4.6	—
	50.0	0.217	4.4	—
	56.8	0.162	4.0	1900
	63.5	0.126	3.7	—
100	43.5	0.217	5.0	1720
	50.0	0.217	6.0	—
	56.8	0.181	5.6	1880
	63.5	0.108	5.0	—
125	43.5	0.217	3.7	1800
	50.0	0.181	3.4	—
	56.8	0.144	3.1	1900
	63.5	0.072	2.2	—

6" DUCTED TAIL PIPE
EJECTOR PERFORMANCE

12½°

FUEL lbs/hr	THRUST lbs	COMB. CH. PRESS. PSIG.	EJECTOR VEL. ft/sec	EXHAUST TEMP. °F
30.5	2.5	0.181	45.9	1860
36.8	4.1	0.289	59.5	1820
43.5	6.5	0.595	66.1	1740
50.0	10.0	0.995	79.5	1610
56.8	11.5	1.190	84.0	1620
63.5	12.8	1.300	85.0	1610
70.0	14.0	1.390	86.6	1560
73.5	13.7	1.120	—	—

RAM AIR TESTS

12 1/2° WITH COWLING

RAM AIR VEL. ft/sec	FUEL lbs/hr	THRUST lbs	COMB. CH. PRESS P.S.I.G.
0	30.5	2.8	0.217
	36.8	4.4	0.325
	43.5	6.8	0.576
	50.0	10.0	1.030
	56.8	11.6	1.190
	63.5	13.1	1.300
	70.0	14.3	1.515
29	30.5	2.1	0.212
	36.8	3.4	0.398
	43.5	5.6	0.614
	50.0	8.7	1.030
	56.8	11.2	1.230
	63.5	13.1	1.480
	70.0	15.0	1.590
52	30.5	1.2	0.199
	36.8	3.1	0.379
	43.5	5.6	0.685
	50.0	8.1	0.992
	56.8	10.9	1.280
	63.5	14.3	1.730
	70.0	15.6	1.810
	76.8	14.3	1.660
75	30.5	0	0.199
	36.8	1.5	0.361
	43.5	3.4	0.685
	50.0	6.8	1.010
	56.8	9.0	1.263
	63.5	13.1	1.700
	70.0	14.3	1.790
	76.8	3.1	—
98	30.5	-1.5	0.181
	36.8	0.2	0.343
	43.5	2.8	0.668
	50.0	5.6	0.975
	56.8	7.5	1.210
	63.5	11.8	1.660
	70.0	13.1	1.770
	76.8	13.1	1.770

12 1/2° WITHOUT COWLING

RAM AIR VEL. ft/sec	FUEL lbs/hr	THRUST lbs	COMB. CH. PRESS P.S.I.G.
0	30.5	1.9	0.144
	36.8	3.4	0.299
	43.5	4.6	0.433
	50.0	6.0	0.577
	56.8	10.0	1.050
	63.5	3.7	0.361
52	30.5	1.2	0.162
	36.8	2.8	0.299
	43.5	4.4	0.590
	50.0	7.2	0.850
	56.8	10.0	1.135
	63.5	11.8	1.335
	70.0	13.1	1.480
29	30.5	2.2	0.180
	36.8	3.4	0.299
	43.5	4.6	0.470
	50.0	6.8	0.685
	56.8	10.0	1.120
	63.5	11.2	1.230
	70.0	4.0	0.361
75	30.5	0.6	0.180
	36.8	1.9	0.306
	43.5	3.4	0.487
	50.0	6.0	0.813
	56.8	8.7	1.120
	63.5	11.2	1.370
	70.0	12.5	1.515
98	30.5	-0.9	0.144
	36.8	0.7	0.299
	43.5	3.1	0.541
	50.0	5.6	0.830
	56.8	7.8	1.082
	63.5	10.3	1.335
	70.0	11.8	1.442